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CONTACT ARC-WELDING

by P. C. van der WILLIGEN.

621.791.753.41

One of the difficulties in electric arc-welding has always been the fact, that the distance between the electrode and the workpiece must be kept constant. It is, however, possible to make electrodes, which can be kept resting on the workpiece, so that the welding can be done by dragging the rod over the workpiece. Philips have now developed a method of touchwelding, whereby the arc is automatically ignited and if necessary reignited. This is achieved by transferring a large part of the metal from the core wire in the form of a fine powder to the originally insulating coating, which thereby becomes more or less conductive. Since the electrode can be kept resting on the workpiece right from the start and, during the welding, is continuously in contact with it both mechanically and electrically, we speak of contact arc-welding and contact electrodes. With these contact electrodes welds can be made quicker and more reliable, than with ordinary electrodes. Furthermore it is also possible to use the free arc with these electrodes.

The method of electric arc-welding widely used to-day, where the deposited material comes from the electrode, which is held close to the workpiece, was first introduced by Slavianoff in 1892. In those days direct current was used exclusively, since, with alternating current of a safe voltage, the arc between the iron electrode and the workpiece was always being extinguished. Only after 1908, after Kjellberg had introduced a coating of slag-forming substances around the rod, was it possible to use alternating current for welding. The coating emits so many electrons, that the welding arc, which with A.C. of 50 cycles is extinguished 100 times per second, continues to burn; or, more accurately, it is reignited 100 times per second. The coating, however, has a still more important function, a metallurgical one. It improves very much the mechanical properties of the deposited metal, which properties are poor when uncoated wire is used. In the course of years this improvement has proceeded so far that the mechanical properties of the deposited material of the most modern electrodes, such as the Philips type Ph 55, are equal to those of the best kinds of structural steel.

As far as welding with A.C. and the mechanical properties are concerned, the introduction of the coating has meant a great advance. Arc welding, however, has always remained an "art", which can only be mastered by much practice. The introduction of the coating has indeed made it easier to do overhead welding. The cup formed during the welding serves to direct the molten drops of metal, just as the barrel of a gun directs the projectile [1]). As to welding in the down-hand positions, however, the coating has scarcely made it any easier. While on the one hand the welder has the convenience of being able to check the speed of travel by following the slag behind the arc, on the other hand the coating and the slag hide the melting-down process and the melting pool from his view.

Touch-welding

The great difficulty in free arc welding has always been in maintaining the arc. The welder must continually take care, that the distance between electrode and workpiece is only a few millimeters and that it remains constant.

When the distance is too small the rod "freezes" to the workpiece, *i.e.* the solidifying drops form a rigid connection. When the distance is too large, the arc burns irregularly and the quality of the work suffers, and with A.C. there is much chance of the arc being extinguished.

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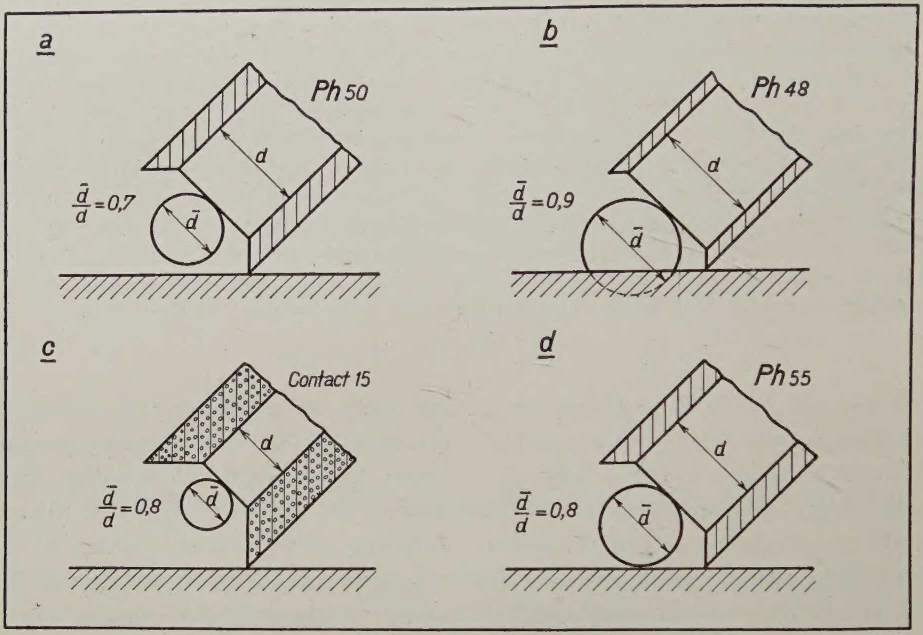
[1]) *Cf.* for example J. Sack, Philips Techn. Rev. **1**, 26, 1936 and **4**, 9, 1939.

In the course of years, however, it has been noticed that with certain types of electrodes the coating can rest on the workpiece during the welding; this is called touch-welding.

It was found that this procedure was only possible with heavily coated electrodes. This can be understood, when one considers that in welding with a rod with a thinner coating only a short cup is usually formed around the arc. When the edge of such a cup is allowed to rest on the workpiece, the drops of metal flowing from the core wire short circuit and freeze the rod to the workpiece.


a
Ph 50
d
$\frac{\bar{d}}{d}=0{,}7$
$\bar{d}$
b
Ph 48
d
$\frac{\bar{d}}{d}=0{,}9$
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c
Contact 15
d
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$\bar{d}$
d
Ph 55
d
$\frac{\bar{d}}{d}=0{,}8$
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Fig. 1. Diagrammatic representation of the possibility or impossibility of touch-welding for different kinds of electrodes manufactured by Philips. The diameter of the iron core is d; $\bar{d}$ is that of the droplet. For the method of determining the size of the droplets see J. Sack, The Welding Industry, July 1939.

If one tries to determine the relation between the thickness of the core wire and that of the coating necessary to prevent this, it is found that it depends upon various factors. If we assume that the welding is done at an angle of 45° to the workpiece and that the cup is formed at an angle of 45° to the axis of the electrode, we see from *fig. 1a* that the relation between the size of drop of the molten metal and the dimensions of the cup is such, for instance with the electrode type Ph 50, that touch-welding is just possible, while with type Ph 48 (see *fig. 1b*) it will be quite impossible.

From this the conclusion might be drawn, that to make touch-welding possible it would be sufficient to give the electrodes a heavy coating. Not only would this, however, be an expensive method, but at the same time difficulties would occur in the welding because of the larger amount of slag.

It is to be pointed out that fig. 1 is only a rough sketch; for instance the formation of the crater (a small dimple in the workpiece underneath the arc) has been disregarded. When high currents are used this crater is rather deep and in that case touch-welding with electrodes of type Ph 50 and 55 easily succeeds. It has never been possible to arrive at a general application of touch-welding because of the limitations just mentioned and some others.

The new development: contact arc-welding

For all these reasons, research work was carried out in this laboratory with the object of perfecting the properties necessary for touch-welding, to such a point, that welding could be done with much less trouble and that practically no errors could be made in welding. This includes the requirement that the weld bead should have a flat and uniform appearance. This investigation has now led to a new method of welding for which the name "contact arc-welding" was chosen, for the reasons which will be explained. We will first sketch the development of this method. Although, in principle, other types of electrodes could have been used in this development, we chose in fact the Ph 55 as starting point, because its mechanical properties surpass those of other types of electrodes (*i.a.* because it has a low oxygen and nitrogen content). Ductility and impact value [2]) are very high. By using the Ph 55, therefore the chance of cracks in the weld is small, which is especially important in welding hard steels and also dynamically heavily loaded structures. For welding hard steels and steel containing much sulphur it is, moreover, important that the electrode Ph 55 is insensitive within wide limits to the content of carbon and sulphur of the workpiece [3]).

The fact that, in spite of all these good properties, the electrode Ph 55 is not universally employed is due to the fact, that much care is required to make good welds with this type of electrode. If, for instance, the welder uses too long an arc, porosity may result in the weld. If a welding transformer is used with a low open voltage (< 60 V) difficulty is experienced from the extinguishing of the arc. The welding is thereby interrupted and has to be started again, which leads to inhomogeneities in the weld.

Therefore, the electrode Ph 55 had to be altered in such a way as to overcome these objections, while still retaining the important advantages mentioned. The first step in this direction was to try to perfect the quality necessary for good touching, without increasing the quantity of slag-forming coating material. This was achieved by applying the principle of making the coating heavier, (which principle, of course, is by no means confined to the use of the Ph 55 rod) by transferring part of the metal of the core in a finely divided form to the coating. The ratio of metal to slag in the welding rod may remain the same. A limit is set, to the transfer of metal from the core to the coating of the rod, by the consideration that the core, which has to carry the current, may not be too thin, as otherwise the resistance becomes too high and the permissible arc current too low.

In the case of the newly developed electrodes, which are denoted by the word "Contact" (thus for example: Contact 15), since they are in continuous contact with the workpiece, about half of the metal of the core is transferred in scattered form to the coating. In *fig. 1c* it is indicated diagrammatically that, with electrode Contact 15, touch-welding should be quite easy. The external diameter of the electrode is more than twice as great as the diameter of the core, so that the coating is extremely heavy. For the sake of comparison we have shown in *fig. 1d* an ordinary electrode Ph 55, which has the same external diameter and the same weight. These two electrodes deposit the same amount of iron in the same time.

Different kinds of electrodes are distinguished not only according to their type, but also according to the thickness of their core, which follows the name of the type. This thickness determines the arc current and in the case of ordinary electrodes also the amount of metal deposited per second. It must be borne in mind that, in the case of the new contact electrode, only half the molten metal comes from the core, the other half being supplied by the coating. In the case of the electrode Contact 15, therefore, the diameter of the core is $\sqrt{2}$ times smaller than that of an electrode Ph 55 depositing the same amount of metal. The new electrode Contact 15-5, therefore, corresponds to the ordinary electrode Ph 55-7.

With the electrode Contact 15 the ignition of the arc has also become much easier. It is not done in the usual way by tapping and breaking off the cup, but entirely automatically. This simplification in starting is closely connected with the new composition of the coating.

In the development of the contact electrodes, as we have seen, much metal has been transferred from the core to the coating. When the amount of metal, transferred to the coating, is approximately the same as that remaining in the core, the conductivity of the coating is found to have become so high that when the coating, under tension, is brushed over the workpiece sparking occurs, such as takes place from the trolleys or shoes in electrical traction when there is icing. A current is then flowing of the order of magnitude of 0·1 A. When the coating is not brushed over the edge, but is held against a definite spot on the workpiece, the current will rise rapidly and at a value of about 1 A will suddenly pass to an arc: the welding arc is then automatically ignited. The oscillogram of the current flowing with Contact 15 is illustrated in *fig. 2*; the arc is usually ignited within one second. When in the hot condition, ignition takes place even more quickly, and obviously the voltage applied also has some influence on the speed of ignition.

Thus the electrode Contact 15 has been made self-starting. Not only has it become unnecessary for the welder to start by tapping, but the reignition, after an interruption of a few cycles, also takes place automatically. Such an interruption

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[2]) P. C. van der Willigen, Philips Techn. Rev. 6, 97-104, 1941.

[3]) J. ter Berg, Philips Techn. Rev. 7, 91-93, 1942.

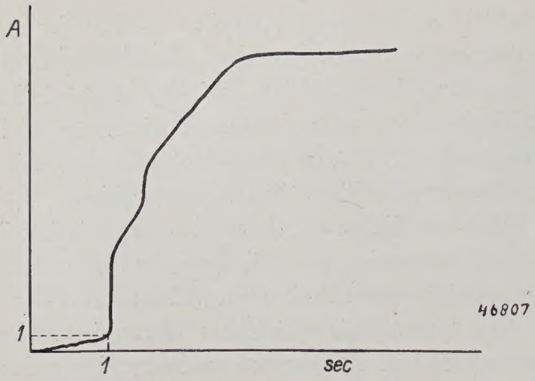

Fig. 2. Oscillogram of the current trend when the arc of Contact 15 is being ignited. The arc is struck at approximately 1 amp. and 1 sec.

may take place accidentally and result in the extinction of the arc, when a welding transformer is used with a low open voltage. The conductivity of the coating of the new electrodes then ensures, that the arc is immediately reignited. As a result with electrodes of the type Contact 15, which have a core diameter of less than 5 mm, it is possible even to touch-weld with open voltages of the welding transformer lower than for the corresponding electrodes Ph 55, *i.e.* they need not be so far above the arc voltages. The contact electrodes 15-3.25 and 15-4, which have core diameters respectively of 3.25 and 4 mm, have for example an arc voltage of 25-30 V, and it has actually been found that touch-welding can, very succesfully, be done with them at an open voltage of 60 V. In some cases, it is found possible to work succesfully at lower open voltages (to 50 V) at which, if the corresponding normal electrodes were used, there would naturally be trouble from extinction. For the new electrodes with core diameters of at least 5 mm (thus corresponding to normal electrodes of at least 7 mm core diameter), however, higher voltages are necessary.

The new electrode Contact 15-5, for instance, has an arc voltage of 40 V. If a welding transformer is used with an open voltage, which lies only slightly above this, the transformer works too much in the flat part of its characteristic, which means, that only small variations in the voltage will already result in large current fluctuations.

The best results are obtained, when the open voltage of the welding transformer lies about 30 V higher than the arc voltages, thus, for the electrodes Contact 15-5, this will be 70 V. Welding then takes place in the steep part of the characteristic, *i.e.* in the part, where the voltage depends closely on the current, so that any variation in the arc voltage scarcely affects the current.

The advantage of contact arc-welding therefore lies in the possibility of easy touch-welding and the automatic ignition and re-ignition of the arc. Moreover, with a given current the amount of metal deposited per unit of time is considerably greater, as will be discussed in a subsequent article.

It has been found, that these new contact electrodes are not only suitable for contact arc-welding, for which purpose they were developed, but that they also offer important advantages for welding with the free arc. The contact electrode gives much less extinguishing of the arc, even when the open voltage of the welding transformer is lower than normal. This is probably the result of the great conductivity of the coating, which now and then touches the pool when the cup is so long.

The use of contact electrodes

It is remarkable, how easy it is to weld with the contact electrodes. This is due not only to the ease of touch-welding, but also to the self-starting. If one must start at a precisely fixed point it is a great convenience, if the starting is automatic, especially when using holders with a push-button mechanism. The welder places his electrode tip on the predetermined spot, puts the shield before his eyes and presses the button (see *fig. 3*). It is a great convenience for beginners too that there is no longer the trouble of tapping and striking the arc.

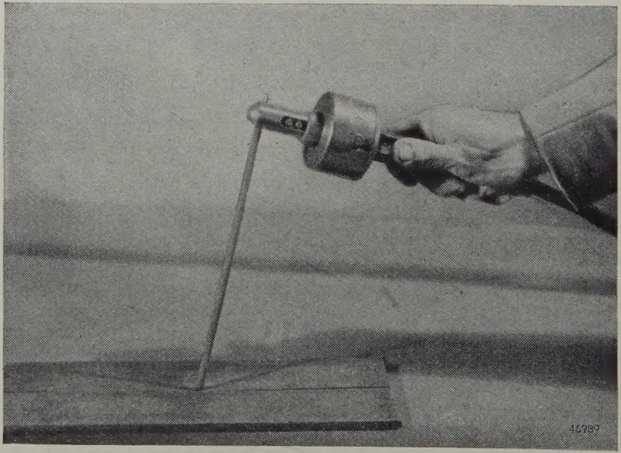

Fig. 3. Photograph of electrode holder specially designed for contact arc-welding. Starting is by pressing the button under the thumb, which closes the circuit.

As we have already stated, practice is necessary in order to maintain the proper distance between

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[4] These two new electrodes would correspond in weight to normal electrodes of the type Ph 55 with core diameters of 4·7 and 5·6 mm respectively, which, however, are not manufactured.

core and workpiece when welding with the free arc, and it is found, that this even presents difficulties for experienced welders, when welding has to be done in difficult positions, so that they too may then have trouble with freezing. With the newly developed electrodes, however, the coating has been made so thick that the cup of the rod is always deep and strong enough to keep the core in touch-welding, at such a distance from the workpiece, that it cannot freeze [5]).

The mechanical properties of the material, deposited [6]) by these new electrodes Contact 15 and Contact 18, are found to be similar to those of the corresponding normal electrodes Ph 55 and Ph 48. The fact that, in the case of the contact rods, the arc is for the greater part surrounded by the deep cup is a favourable factor, diminishing the absorption of oxygen and nitrogen from the air.

While it is usual to weld from left to right, welding from right to left also often occurs in practice, and left-handed welders were desired for such work. With contact electrodes this work, which is no more difficult than melting a candle at a uniform rate against a hot plate, can also be done by right-handed welders, namely with the back of the hand turned towards the workpiece, called "backhand" welding, or by holding the holder in the left hand, which, in the case of the more difficult normal welding can, only be done succesfully by left-handed welders.

Just as with normal electrodes, with contact rods care must also be taken to prevent the slag running ahead of the arc. To accomplish this, in contact arc-welding, the angle between electrode and workpiece must not be too large. In the down-hand position an angle of 40 to 45° is best. If a smaller angle is chosen there is more sputter. Another disadvantage of a very small angle is, that the arc does not "dig" so well into the root of the weld, which is often of importance, when using these rods with deep cups. In practice, it sometimes happens that it is impossible to maintain the desired angle of 40 to 45°; for instance because of the proximity of a transverse partition. It is then possible, to weld from right to left or to use the free arc. One can then weld in such a way that the slag remains behind the arc, although the rod makes a large angle with the workpiece.

The most convenient position for making a welded joint is the flat position, where the surface of the bead is in the horizontal plane (*fig. 4*). In this position the heaviest electrodes can be used without difficulty. This is true, not only for the methods of welding so far commonly applied, but also for contact arc-welding, with which very fine results can be obtained. *Fig. 4* shows two fillet welds made with Contact 15-5, on the left with 360 amp. A.C. on the right with 310 amp. D.C.

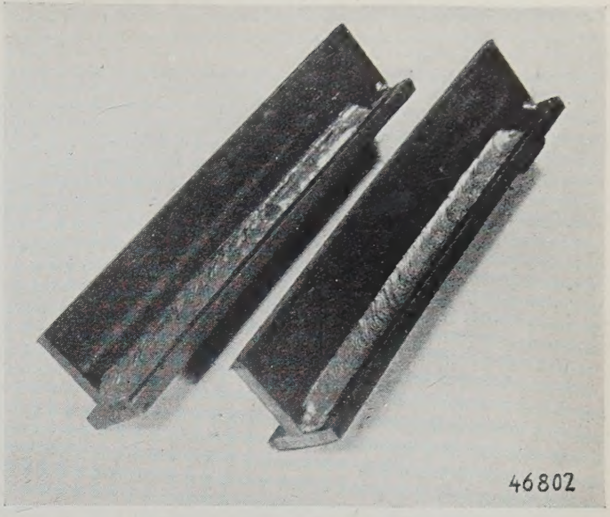

Fig. 4. This photograph shows two fillet welds made in the flat position with Contact 15-5; that on the right, made with D.C., has a smoother surface than that on the left made with A.C.

For fillet welds, made in the horizontal position, where one plate is horizontal and the other perpendicular to it, Contacts 15-3·25 and 15-4 can be used. With heavier electrodes the weld is strongly convex in form.

A most remarkable achievement is the ease with which overhead welding can be done [7]), with Contacts 15-3·25 and 15-4. This is the most difficult position for welding, and, as far as is known, it was never possible to apply touch-welding with success in this position. Overhead contact arc-welding, however, is found to be very easy. *Fig. 5* is a photograph of a weld made in this position with Contact 15-3·25 and using 140 amp. D.C. In overhead welding experienced welders sometimes prefer to use the free arc, for instance in order to make the weld

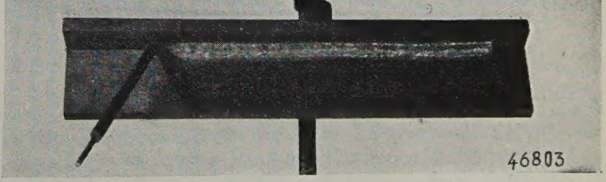

Fig. 5. Overhead weld made with Contact 15-3·25.

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[5]) In the special case, where the electrode is cooled after being partly used, it may happen that non-conducting slag is formed on the edge of the cup and prevents the arc from starting. This slag can, however, very easily be broken off by tapping.

[6]) See the article cited in footnotes [1]) and [2]).

[7]) *Cf.* for example Philips Techn. Rev. 4, 9, 1939.

somewhat wider by means of a weaving motion. Also in this respect Contact 15 offers advantages over the normal coated electrodes, the most important of which results from the deep cup of Contact 15, which gives better direction to the drops; consequently very little material falls to the ground. When, however, Contact 15-5 and larger sizes are used, the pool becomes too large and the molten iron falls out of it, so that Contact 15-4 is the heaviest electrode that can be used for overhead welding.

In work on ships it is often necessary to make a horizontal weld in the vertical plane (the ship's side). This work can be done very well with Contacts 15-3·25 and 15-4. In vertical-up positions the electrode should, in general, be moved sideways (weaving) perpendicular to the direction of the weld, in order to obtain a sufficiently wide bead, the fused material being left to solidify at the desired spot; thus the great advantage of contact arc welding, namely that no precisely regulated motions need be made, does not apply in this case. In vertical-up welding, therefore the free arc will always be used, but the electrodes already mentioned can be used here to advantage. *Fig. 6* shows a good vertically-up weld made with the free arc using Contact 15-3.25 and a welding transformer with an open voltage of only 50 V. In vertical-down welding Contact 15 generally gives rise to an excessive amount of slag. The welder must try to keep the slag above the welding arc, because, if it is allowed to run down, it pushes the arc and the molten metal aside, resulting in faults in the surface of the weld. For these reasons a contact electrode has been developed with a thinner coating, namely Contact 18. Taking as basis Ph 48, which is very much used for vertical-down welding, the same principle has been applied here as in Contact 15. Thanks to the small amount of rapidly solidifying slag, it is easy with Contact 18 to keep the slag above the welding arc. Welds made in this manner have a particularly good appearance. Since the surface of the bead is very smooth, the slag often loosens of itself. This contact electrode, like Contact 15, is suitable not only for D.C. but also for A.C. The weld of *fig. 7* was made with the help of Contact 18-4.

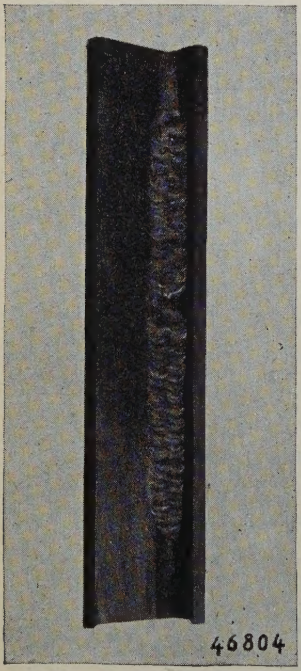


Fig. 6

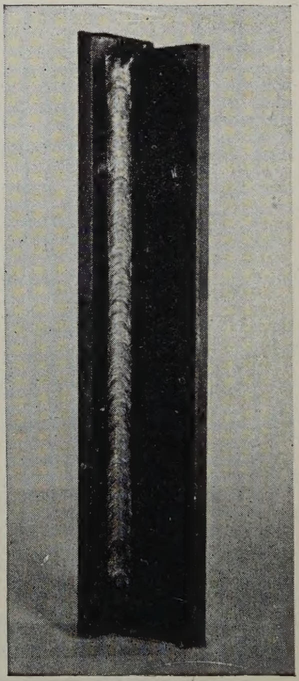


Fig. 7

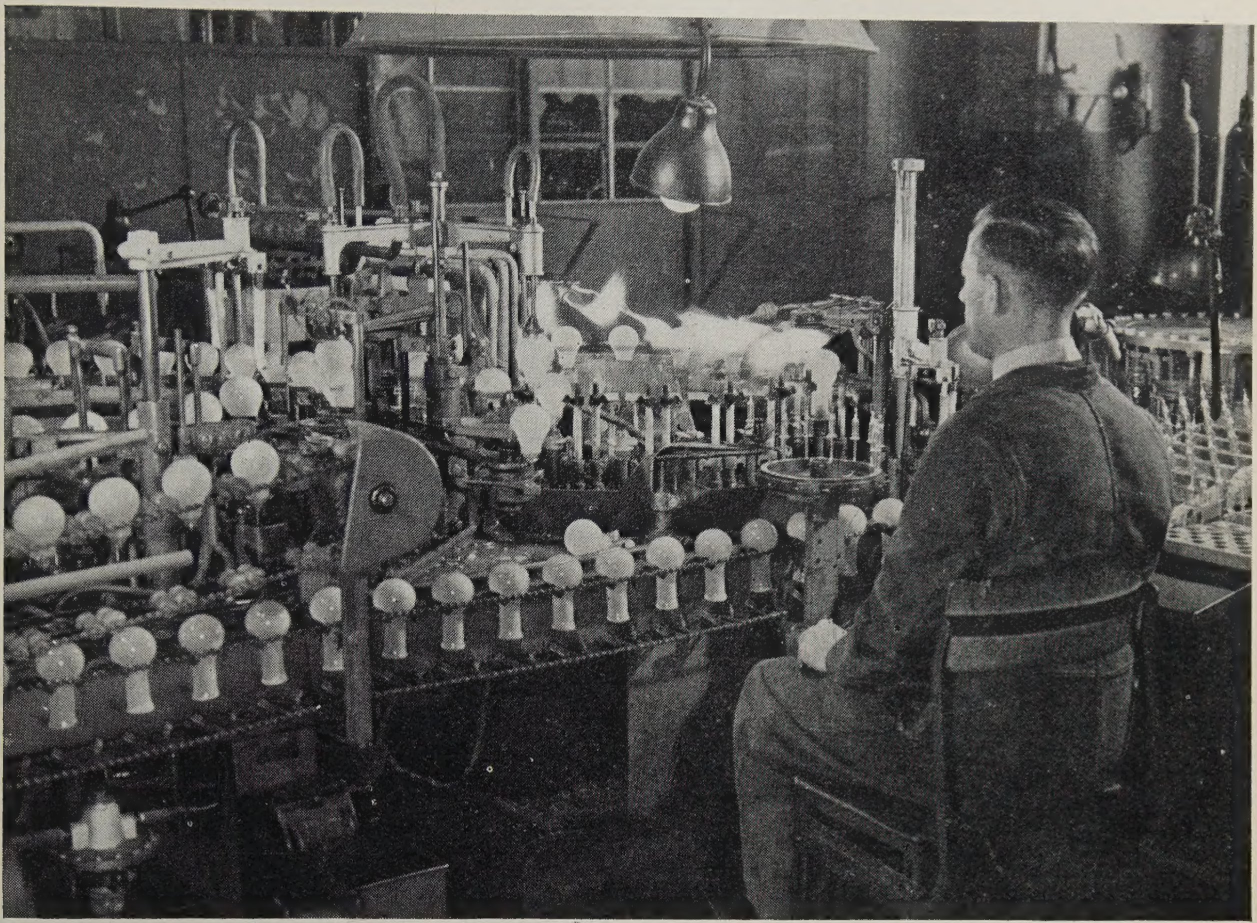
Fig. 6. Vertical-up weld made with the electrode Contact 15-3·25. In this case the free arc was used, since contact arc-welding offers no advantage here, where the welding has to be done with a weaving motion. The open voltage of the welding transformer was only 50 V.
Fig. 7. Vertical-down weld made with Contact 18-4, which has a thinner coating.

In conclusion, we shall make a few remarks about welding with high currents, where heavy welding rods are used, and which in the United States is called "hot welding". The currents used are higher than 600 amp. and the diameters of the electrodes greater than about 7 mm. As yet, however, this method has not met with much success, for the following reasons:

a) Handling heavy electrodes becomes fatiguing for the welder.
b) There is much spatter with these rods.
c) Heat radiation becomes troublesome, especially in hot weather.
d) Difficulty is very often experienced from undercut, the plate material being burnt away along the toe of the weld.

If Contact 15-6, 15-8 or 15-10 is used for this purpose (the last corresponds to Ph 55-14 and is used with 900-1200 amp.), the first difficulty is overcome, since in contact arc-welding the electrode rests on the workpiece. Due to the deep cup shielding the arc, also spatter is considerably reduced; tests showed spatter losses only one-third of those obtained with the corresponding electrode Ph 55. For the same reason, heat radiation from the arc is lowered, especially in the direction of the weld, since in that direction the cup almost completely shields the arc. Finally with Contact 15 undercut is eliminated as a result of the special form of the penetration, to be discussed in a later article.

SERIAL GROUP FOR THE MANUFACTURE OF INCANDESCENT LAMPS



An incandescent lamp factory originally comprised a number of departments housed in large workshops, where the various stages of the manufacturing process were entirely separate from each other. The stages were: the construction and mounting of the stem, *i.e.* the internal glass part with current leads, pump tube and filament; the sealing of the base in the bulb along the lower flanged rim; the lamp thus built up then has to be evacuated or filled with gas (Argon), during which process the lamp was heated to degas the component parts; finally in a fourth department the base was cemented to the lamp.

Obviously, in course of time these processes became highly mechanised. There were certain advantages attaching to the separation of manufacture among different workshops, owing to the specialization of certain parts of the processes. The drawbacks, however, among which was the transport problem, were much weightier; for instance a great deal of administrative work and care was required in order to keep together the various parts of a certain type of lamp in passing from one shop to another.

The photograph reproduced here shows how all this has been changed. All the processes mentioned are combined in this one single unit, called the serial group. The conveyor, clearly seen in the foreground, brings in the bulbs. Mechanical hands automatically pick up a bulb and a mounted stem and place them together on the sealing machine. This machine rotates and takes up a number of positions, in each of which a certain part of the sealing of stem to bulb takes place on the turntable immediately underneath the lamp. The part of the machinery on the left of the photograph is where the pumping, gas-filling and further finishing is done.

Such a serial group turns out a complete lamp of a certain type with the minimum of manual labour, all the component parts being assembled together automatically, while the various operations are arranged in the proper sequence by a very carefully studied timing.

SIGNALLING IN CARRIER TELEPHONY

by F. A. de GROOT.

621.395.63:621.395.44

The establishing of a connection between two subscribers of a telephone network requires the transmission of different signals from the subscribers' instruments to the exchange and *vice versa*. In local networks this signalling is done partly with direct current. Since, however, in the case of long trunk lines, and especially in the case of carrier connections, this is impossible, other methods had to be developed. After a short discussion of signalling with alternating current of audio-frequency, the Philips system of signalling with the carrier waves is considered. In the description of the practical execution of this method of signalling special attention is devoted to the manner, in which interferences with the signal and by the signal are avoided, and how the distortions, which the signals may experience upon transmission, can be counteracted.

In order to carry on a telephone conversation, it is not enough to have available an installation which is capable of transmitting speech clearly and without interferences. Each subscriber must also be able to ring up any other subscriber. To do this, he must be able to inform the telephone exchange, that he wishes a call to be put through; the exchange must prepare the connection, warn the subscriber called, inform the subscriber calling, whether or not the desired line is already engaged, etc.; finally after the conclusion of the conversation the exchange must be warned, so that everything can be returned to a position of rest.

All these and any other warnings and communications are accomplished by certain signals, and the complex system of aids, which serve for the excitation and transmission of these signals, is called the signalling system.

A signalling system is necessary, not only for local, but also for trunk connections. The problems thereby involved, especially when carrier telephony is used for the trunk connection, will be discussed in this article. We shall deal especially with a signalling system, developed by Philips, in which the carrier waves themselves are used for the signalling. We shall begin with a simplified description of what happens, in a local telephone conversation, between two subscribers on an automatic exchange.

Signalling in a local connection with automatic exchange

In *fig. 1* the circuit diagram is given of the connection between two subscribers a and b, omitting all non-essential details.

In the state of rest, the telephones of the two subscribers hang on their hooks, the contacts H_a and H_b are then open, the lines carry no current, the relays R_a and R_b are released. Upon a lifting up the receiver, the contact H_a is closed and a direct current I_a, furnished by the battery E, begins to flow through the line and the apparatus. This direct current (which, moreover, also serves to feed the carbon microphone M) energizes the relay R_a and the exchange is by this means informed, that a wishes to make a call. The exchange, by means of a switching process, which may be disregarded here, now makes itself ready to "hear", with whom a wishes to speak. The fact, that the exchange is ready for this, is communicated to a by a so-called dialling tone, which is sent over the line by the exchange. Upon hearing this, the subscriber begins to dial, *i.e.* he turns his dial and lets it run back; during this running back the line current is interrupted (by means of the cam N and the contact K), this being repeated as many times as there are figures in the number dialled. Upon each interruption, the relay R_a releases and thus passes the impulses through to the automatic selectors set up at the exchange, which thus select the line of the subscriber being called. As soon as this line has been found, it is ascertained, whether it is free (by whether its relay R_b is "up" or not). If it is not free, the exchange sends over the line to a the "engaged" signal. If the line is free, the exchange sends an alternating current with a fundamental frequency of 16 c/sec to b, the so-called ringing current. The hook contact of this subscriber is of

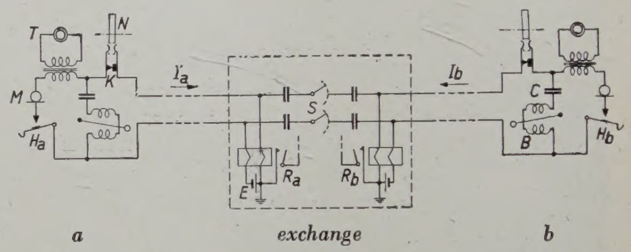


Fig. 1. Simplified diagram of the signalling system in a local telephone connection with automatic exchange. M microphone, T telephone, H_a and H_b hook contacts, B bell, C condenser, N cam disc, K contact of dial, I_a and I_b line currents, R_a and R_b relays, S selectors.

course open, but the alternating current passes the condenser C, which is tuned with the self-induction of the bell to 16 c/sec and causes the bell to ring. At the same time the exchange sends a ringing tone over the line to subscriber a, as a sign, that b's bell is ringing. As soon as b removes the receiver direct current also begins to flow in his line, the ringing is stopped by the operation of the relay R_b and the conversation can take place. When the conversation is ended, the subscribers hang up their receivers again, the direct current in the two lines is thereby interrupted, the relays R_a and R_b are released and as a consequence the selectors and the various relays in the exchange return to their position of rest.

In *fig. 2* all these happenings are represented graphically, by the variation with time of the currents I_a and I_b on the lines of the subscriber calling and the subscriber called respectively. It is seen that the signalling comprises the following signals [1]):

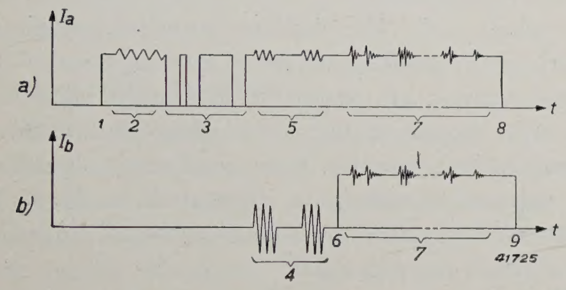


Fig. 2. Behaviour of the line currents I_a and I_b during a telephone call. *a*) Line of the subscriber making the call, *b*) line of the subscriber called. *1* Calling signal, *2* dialling signal, *3* dialling impulses, *4* ringing current, *5* ringing tone, *6* answering signal, *7* speech currents, *8* and *9* clearing signals.

The calling signal (*1*) switching on the direct current I_a).

The dialling tone (*2*).

The dialling impulses (*3*) interrupting the direct current I_a.

The ringing current of 16 c/sec (*4*).

The ringing tone or engaged tone (*5*).

The answering signal (*6*) switching on the direct current I_b.

The clearing signal (*8-9*) switching off I_a and I_b.

Signalling in trunk traffic

More and more use is being made of automatic dialling, also for trunk traffic. In the Netherlands, for example, the telephone network in important parts of the country has already been made automatic. In principle, the manner of establishing the connection is the same, as described above, for a local call. Suppose, that the subscriber a in A wishes to speak with subscriber d in D. He lifts up the receiver, waits until he hears the dialling tone of his local exchange A and then dials a certain number, upon which the local exchange connects him with the trunk exchange B (see *fig. 3*).

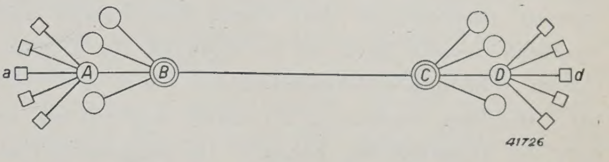


Fig. 3. Diagram of a trunk connection between subscriber a connected with the local exchange A and subscriber d connected with the local exchange D. Various neighbouring local exchanges are connected with a trunk exchange (B and C). The line, between local exchange and trunk exchange, is still considered as "local" line. Between the trunk exchanges B and C, which are far apart, lies the trunk line proper.

In this exchange, as a result of new dialling impulses, the selectors find a line to the trunk exchange C. As soon as this line is found, a warning is sent to C (a new calling signal). The subscriber now continues to dial and the impulses, then following, have to be transmitted over the trunk line to C, to cause the selectors there to transmit to a line, connecting C with the local exchange D. This exchange now sends the dialling tone back to subscriber a, who now with his dial sends impulses over the whole connection to the selectors in D, which find the line of subscriber d. The exchange D then sends the ringing current to d in the manner already described and at the same time the ringing tone or the engaged tone, as the case may be, is sent back to a. After the conclusion of the call, a clearing signal from B to C (or *vice versa*) is again necessary to break the connection and bring the apparatus back to the position of rest [2]).

It is thus clear, that practically all of the signals mentioned for local connections have to be transmitted also over the trunk line: calling signal, dialling impulses and clearing signal as signals intended for the apparatus, further dialling tone and ringing or engaged tone as signals intended for the ear of the caller, to let him know what the situation is [3]).

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[1]) In addition to those mentioned here, there are other signals, such as those for counting the calls, measuring the duration of a call, etc. Since these do not involve anything new in the problems to be considered here, they will be left out of consideration.

[2]) The course of events sketched here is characteristic of the so-called direct system. There exist also other dialling systems (registering systems), but the signals they require are in principle the same as those with the direct system.

Different methods of signalling

We have seen that for signalling on the local line, as far as the signals intended for the apparatus are concerned, use is made of direct current, which is in any case required for the microphone. Direct current is also used for short-distance trunk connections. For long-distance connections, however, it is difficult to obtain a satisfactory solution in this way: the transformers and any necessary repeaters in the line cannot transmit the direct current directly, so that every transformer and amplifier would have to be shunted by a relay system. Through coil-loaded cables, which are often used for long distances, no direct current at all may be transmitted, because the magnetization thereby caused is detrimental to the properties of the loading coils.

In carrier telephony too, direct current cannot be used for signalling, because here a number of calls are sent through one pair of conductors and only one direct current can be sent through a pair of conductors. The signals therefore have to be transmitted in some other way, and, for every speech channel, there has to be a signal path independent of the other channels.

The method so far commonly used in these cases is voice-frequency signalling. The D.C. signals occurring on the local line are converted in the trunk exchange into A.C. signals with a frequency in the audible region, between 300 and 2800 c/sec. Since the trunk line must in any case transmit this frequency region, either directly or modulated on a carrier wave, the A.C. signals can be immediately passed on over the trunk line. At the receiving end the signals are converted back into D.C. signals by filtering out the signal frequency and activating a relay with the signal voltage.

In voice-frequency signalling the calling and clearing signals, which occur on the local line, when the direct current is switched on and off respectively, cannot be transmitted in the form in which they occur as the result of the switching on and off of the alternating current, because this alternating current would then have to be maintained during the whole conversation and would be heard by the subscribers as a disturbing whistle. Calling and clearing signals are therefore now given by A.C. impulses of a certain length. One speaks in this case of impulse signalling in contrast to continuous signalling with a direct current, where the signal current continues to flow during the whole call. The dialling impulses, which in continuous signalling consist of interruptions of the signal current, are passed on in impulse signalling by A.C. impulses, like the calling and clearing signals. The transition from continuous signalling to impulse signalling is illustrated in *fig. 4*. In practice, it is realized by a combination of a number of relays, a relay group.

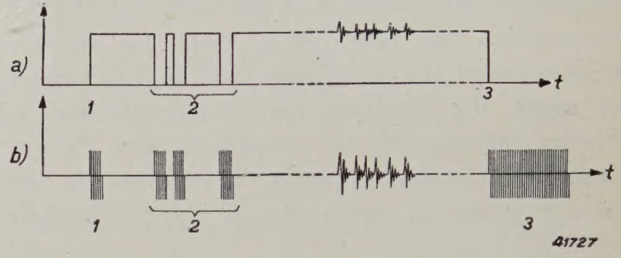

Fig. 4. Transition from continuous signalling with direct current (*a*) to impulse signalling with voice-frequency alternating current (*b*). *1* Calling signal, *2* dialling impulses, *3* clearing signal.

The relay groups make the signalling more complicated and increase the chance of interferences. Besides this complication, however, there is also a fundamental difficulty in the method of voice-frequency signalling. Owing to the fact, that the signalling frequency is chosen in the frequency region of speech, it is possible that the signalling

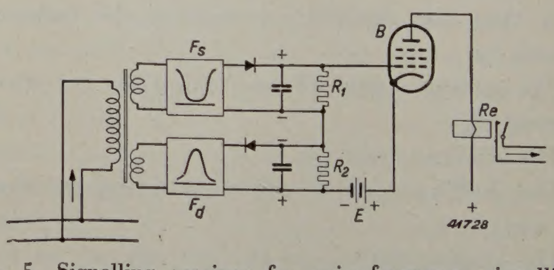

Fig. 5. Signalling receiver for voice-frequency signalling. The instrument has to distinguish, whether an input voltage with the signalling frequency originates from a signal, from speech or from interferences. For this purpose the input voltage is fed to two filters F_s and F_d connected in parallel. F_s passes the signalling frequency through and damps the other frequencies, F_d damping the signalling frequency and passing the others through. The output voltages of the two filters are rectified and fed with opposite polarity to the control grid of the amplifier valve *B*. Due to the negative bias from the battery *E*, the amplifier valve does not transmit any anode current, so that the relay *Re* is released. When a current with the signalling frequency arrives, a positive voltage occurs over R_1, the valve begins to carry current and *Re* reacts. If, however, other frequencies arrive, simultaneously with the signalling frequency, a negative voltage will occur on R_2, and if this is equal to or greater than the voltage on R_1 the valve *B* remains "overbiased" and *Re* does not operate.

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[3]) A connection between two manual exchanges, as far as the signalling is concerned, is often simpler than one between two automatic exchanges, since there are no dialling impulses nor signals intended for the ear of the subscriber calling. The calling and clearing signals are still necessary, since it is impossible to have an operator listening on each line all the time. It is the dialling impulses, however, that cause the greatest technical difficulties, as we shall see.

receiver also reacts to the speech voltages themselves: if the signalling frequency occurs in any intensity in a speech sound the receiver may, for instance, construe this as a clearing signal and break the connection prematurely. In order to prevent this, the signalling receiver must be so constructed, that it can distinguish, whether a voltage with the signalling frequency originates from signal or from some other source. Use is often made here of the fact that in speech different frequencies always occur at the same time, whereas, in signalling only the signalling frequency occurs. The voltages with other frequencies are then used to put the signalling receiver out of action with the help of connections, which are shown in *fig. 5* and explained in the text underneath. This arrangement works satisfactorily, but it has the great drawback, that current surges or loud speech may cause the signalling receiver to be blocked, as a result of which impulses are lost or distorted.

Carrier wave signalling

While the method of voice-frequency signalling described, can be used for normal (low-frequency) as well as for carrier telephone connections, the method, about to be discussed, is especially intended for carrier telephony. With this method, which was developed by Philips several years ago, reaction to speech is out of the question.

In carrier telephony the speech vibrations of each call are fed to a modulator, together with a carrier wave of higher frequency. The modulator converts the speech vibrations into side bands of the carrier wave, but, thanks to suitable connections, does not allow the carrier wave itself to pass, or at least not to any extent worth mentioning [4]). The carrier wave itself is thus not transmitted over the line. In order to be able to bring the transmitted side band — only one is transmitted since the other is suppressed in the transmission band filter — back into the original frequency region, the carrier wave is added again in the demodulator at the receiving end.

In the new method of signalling, the carrier wave frequency of each telephone channel is used for signalling in that channel. Separate oscillators for the excitation of the carrier wave frequencies are not required, as the carrier waves are also necessary for the modulators (and demodulators) and are therefore already excited in the exchange [5]). By means of a transmission relay, the carrier wave can be applied in each channel to the line behind the modulator. At the receiving end a selective receiver is connected in parallel with the demodulator, which receiver amplifies and rectifies the carrier wave. A receiving relay is operated by the D.C. voltage obtained, and this relay passes the signals to the respective apparatus in the automatic exchange.

For this method, therefore, a frequency is used, which does not occur in the modulated speech spectrum, and which gives no audible tone after demodulation. In the first place, this makes it possible to use continuous signalling as is done in local telephony by means of direct current (the carrier wave itself may in fact also be considered as "displaced direct current" of the corresponding channel). As a result the above-mentioned relay groups are made much simpler. On the other hand, continuous signalling, as we shall see later, is also accompanied by drawbacks connected with the necessary limitation of the permissible signal intensity. If, for this reason, impulse signalling is after all preferred, there still remains the important advantage, that the reaction of the signalling receiver to speech need not be feared in principle, since the carrier wave frequency does not occur in the modulated speech. (The speech currents of the neighbouring channels, which, in principle, may contain the carrier frequency of the channel first considered, are already kept out of the channel by the filters in order to prevent cross talk, and so they cannot disturb the signalling receiver either.)

In the practical realization of carrier wave signalling, the following requirements must be kept in mind:

1) The signalling must not cause any disturbance of the speech (or the signals) of other channels.
2) The signals must be transmitted undistorted.

The second requirement is especially important in connection with the dialling impulses. These impulses are given, for instance, at a rate of 10 per second, each impulse lasting twice as long as the interval between two impulses (see *fig. 4*). In order to ensure reliable functioning of the selectors in the automatic exchange, only certain deviations from the nominal duration of the impulses are permissible. These tolerances, however, are for the greater part already consumed by the rest of the apparatus, for example by the variations in the turning of the dial of the subscriber's instrument. Thus, for trunk connection, it is essential that the length of the dialling impulses supplied at the beginning should be reproduced in the receiving station, with not more than several thousandths of a second deviation.

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[4]) See: F. A. de Groot and P. J. den Haan, Modulators for carrier wave telephony, Philips Techn. Rev. 7, 83, 1942.

[5]) See: D. Goedhart and G. Hepp, Philips Techn. Rev. 8, 137, 1946.

On the basis of the requirements mentioned, we shall now discuss the practical realization of carrier signalling.

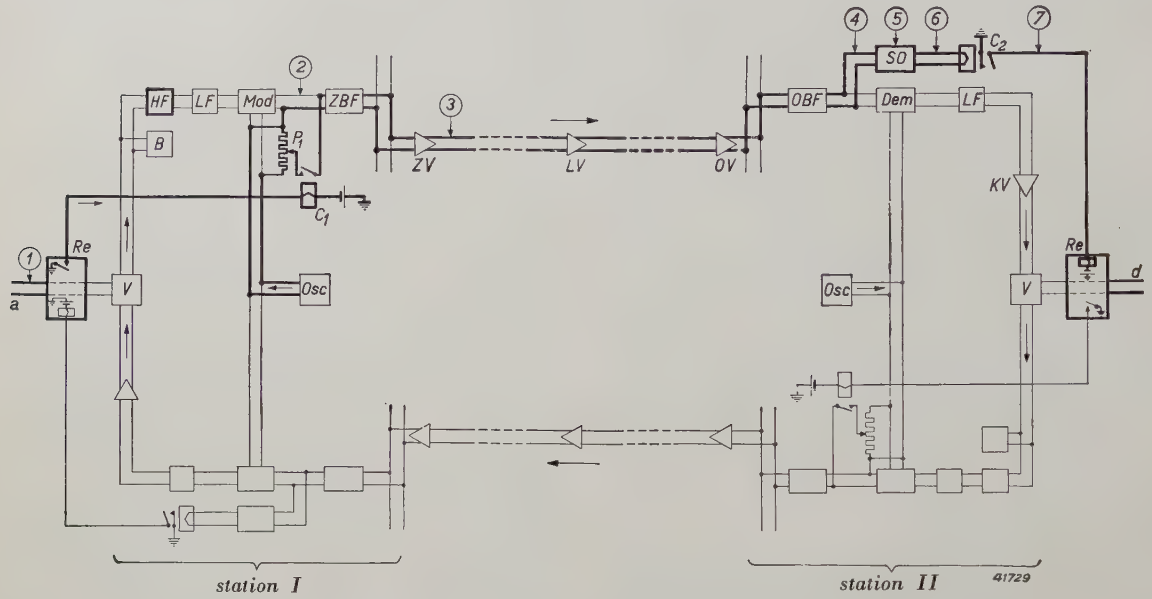

Fig. 6. Simplified diagram of one channel of a carrier telephone connection between two stations *I* and *II*. The components, added for signalling, and the path of the signals are indicated with heavy lines. At *a* (or *d*) the "local" line comes in. *Re* relay group. *V* four-wire termination, *B* limiter, *HF* high-pass filter, *LF* low-pass filter, *Mod* modulator, *Osc* generator for the carrier wave, C_1 transmitting relay, *P* potentiometer for regulating the intensity of the carrier signal, *ZBF* transmitting band filter, *ZV* transmitting amplifier, *LV* line repeaters. *OV* receiving amplifier, *OBF* receiving band filter, *SO* signal receiver, C_2 receiving relay, *Dem* demodulator, *KV* channel amplifier.

Practical execution of carrier signalling

Avoidance of interferences

Fig. 6 represents, in the form of a block diagram, the apparatus for one channel of a carrier telephone connection, the heavy lines indicating the path of the signals and the components added for the signalling.

As may be seen in the diagram, the carrier signals are not fed directly to the common line but (with the help of the relay C_1) to the input of the transmission band filter. This is necessary, in order to avoid interferences in other channels. The dialling impulses, which are sent through the relay, may be considered as a carrier wave, modulated with a sort of block-shaped curve with a fundamental frequency of 10 c/sec. The harmonics of this frequency, of which the block-shaped Fourier curve is built up, occur as side-band frequencies of the carrier wave and these side-band frequencies fall partially in neighbouring channels (*fig. 7*). A closer examination shows that, for instance the 250th harmonic (2 500 c/sec) which, with a carrier spacing of 4 000 c/sec between two adjacent channels, gives in the lower channels after demodulation a tone of 1 500 c/sec, lies about 50 dB below the speech level. This of itself is not very disturbing, but, due to the fact, that several hundred of these harmonics fall within the speech band, there occurs in the aggregate an intolerably strong interference. All the side-band frequencies, which would fall in other channels, are now damped by the transmission band filter, as may be seen from the filter curve in fig. 7.

At the receiving end may be seen in fig. 6 the

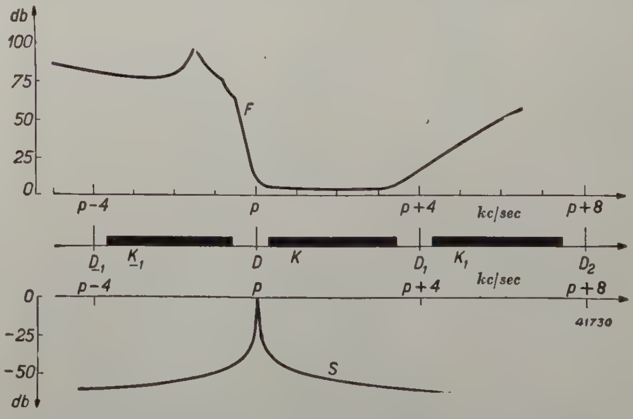

Fig. 7. Damping curve *F* of the transmission band filter of a channel, *D* carrier wave, *K* frequency region, that has to be transmitted for the speech in this channel; in addition the corresponding frequency regions and the carrier waves of several neighbouring channels are indicated. *S* amplitude of the harmonics of the dialling impulses for the channel in question *K*; the harmonics have a spacing of 10 c/sec. Each third harmonic has the intensity zero, but this fine structure cannot be seen in the drawing.

signalling receiver (SO), which upon reception of a signal activates the relay C_2. In order to prevent the receiver from reacting also to the speech voltages, it must contain a sharp filter for the signalling frequency. So as to avoid having to construct a receiver with a different filter for every channel, which is not very well feasible either for the designing, for the manufacture or the operation of the installation, the incoming signal (frequency p) is modulated in the receiver with an 8 kc/sec higher or lower frequency ($p \pm 8$), this giving rise, *i.a.*, to a difference frequency of 8 kc/sec. This is filtered out and fed to an amplifier and rectifier (*fig. 8*). In this way the same filter, namely for 8 kc/sec, can be used for all channels. This filter has the damping curve reproduced in *fig. 9*. It is seen, that already at a distance of 300 c/sec from the signalling frequency the damping amounts to more than 30 dB, while the speech band proper only begins here.

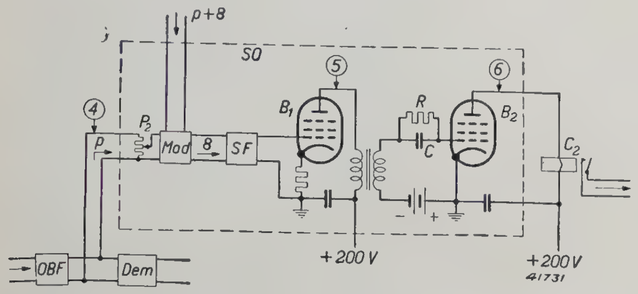

Fig. 8. Connections of the signalling receiver SO. P_2 potentiometer for regulating the intensity of the input signal, *Mod* modulator, *SF* filter for 8 kc/sec, B_1 amplifier valve, B_2 detector valve.

The reason why a frequency of 8 kc/sec is used is easy to understand. In the first place the frequencies $p \pm 8$, necessary for modulation, coincide with the carrier waves of other channels and are thus available in terminal stations of the installation without further auxiliary apparatus. In the second place it is an advantage to choose the difference frequency low, as the filter curve can then be made relatively less narrow: an absolute width of the transmission region of 600 c/sec at a signalling frequency of 60 kc/sec means a relative width of 1 percent, whereas at 8 kc/sec it means a relative width of 7.4 percent, which is much easier to realize.

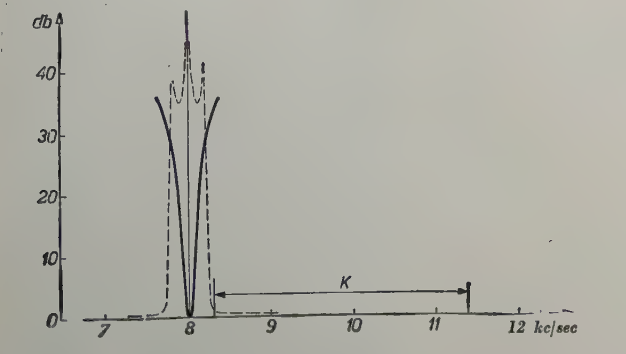

Fig. 9. Damping curve of the filter for 8 kc/sec in the signalling receiver. K is the frequency band of the corresponding speech channel. The broken line curve is the damping characteristic of the high-pass filter to be described later, shifted to 8 kc/sec.

Since the carrier spacing normally amounts to 4 kc/sec, it might really have been better to use a difference frequency of 4 kc/sec, but this was not done for the following reason. The carrier frequency p, after modulation with $p + 8$, gives in the signalling receiver the difference frequency 8 kc/sec. But the carrier frequency $p + 16$ ("mirror frequency"), which belongs to the speech channel lying four channels higher and which transmits the signals for that channel, also gives in the receiver, first considered, the difference frequency 8 kc/sec, so that the receiver would also react to that. In order to prevent this, the signalling receiver is not connected directly with the line, but is placed behind the receiving band filter of its channel (see the diagram of fig. 6) or, more precisely, behind the first sections of the receiving band filter, in order not to expose the signals to the full damping, which that filter produces for the carrier frequency. The filter has, in the main, the same damping curve as the transmission band filter (fig. 7). The damping of the sections in question at $p + 8$ is not yet so great as to preclude entirely reaction of the receiving relay to a signal with this frequency, which danger threatens, when a difference frequency of 4 kc/sec is used. At $p + 16$, however, the damping is so great, that there is no danger of this.

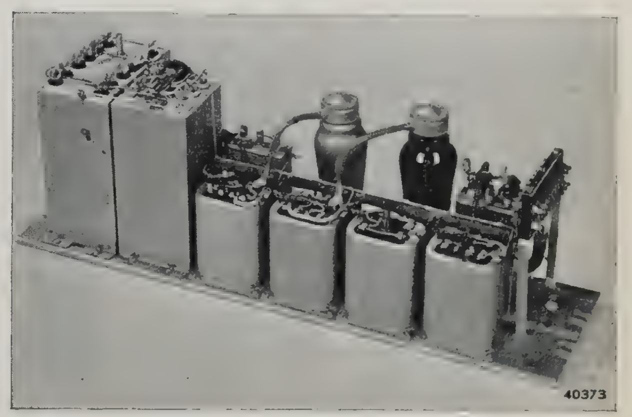

Fig. 10. Signalling receiver. On the left the modulator and the filter, on the right at the rear the two valves.

In *fig. 10* a photograph is shown of the signalling receiver described, while *fig. 11* shows a bay with signalling receivers and appurtenances, for a carrier installation for 17 channels.

Distortion of the signals

We have seen that the carrier signals must pass through the transmission band filter and the receiving band filter, among others. These filters suppress the side-band frequencies, which fall in their damping region, and also cause a relative attenuation of those frequencies, which fall in the transition region between damping and transmission, namely the carrier wave itself and the 30 lowest harmonics of the dialling impulses. This results in a certain (slight) distortion of the dialling impulses, as may be seen in the oscillograms of *fig. 12.* The first oscillogram shows the dialling impulses, as given with direct current (point *1* in fig. 6). The second oscillogram gives the voltage in front of the transmission band filter; during the time that the incoming line is not carrying current the carrier wave is transmitted (transition from the continuous to impulse signalling). These carrier impulses are practically rectangular. The third picture shows the impulses behind the transmission band filter, amplified in the transmission amplifier. Some rounding off has taken place. In the case of the input signal of the signalling receiver, oscillogram no. 4, the rounding off has become somewhat greater, owing to the influence of the receiving band filter.

The most important distortion, however, occurs in the following step: the filtering out of the 8 kc/sec frequency by the sharp filter in the signalling receiver. Here, since it is a question of eliminating the speech frequencies, the higher harmonics of the dialling impulses are attenuated. At 300 c/sec, *i.e.* the 30th harmonic, the damping of this filter, as already mentioned, is 30 dB; but also the 5th harmonic, for instance, is already attenuated by 6 dB. The resultant considerable rounding off of the impulse may be seen in the fifth oscillogram of fig. 12.

What is in fact of importance with dialling impulses is the need to keep to their correct length. A closer examination of the functioning of the signalling receiver (fig. 8) shows, to what extent errors may occur in this length, as a result of the rounding off of the impulses. After passing the filter the signals are amplified and fed to a valve (B_2) acting as anode detector. The I_a-V_g characteristic of the valve (anode direct current as a function of the grid A.C. voltage amplitude) is drawn in *fig. 13.* The fixed negative bias $-V_0$ of the grid is chosen so large, that plate current only begins to flow at several volts signal voltage. (This threshold voltage, below which the receiver does not work at all, gives an extra security against slight interferences, such as the carrier leak of the modulator at the transmitting end.)

With a sufficiently intense signal, plate current begins to flow; the relay C_2 will react as soon as the plate direct current has reached a value of 3 mA. The impulse transmitted thus becomes rectangular again in any case, but what about its length? In fig. 13 the variation of the grid A.C. voltage amplitude is drawn for the case, where the rounded off dialling impulses, reaching the grid, have the form of oscillogram no. 5, dialling impulses of three different intensities being assumed. The length of the original impulse is *AB* in all three cases. In the case of the weak sig-

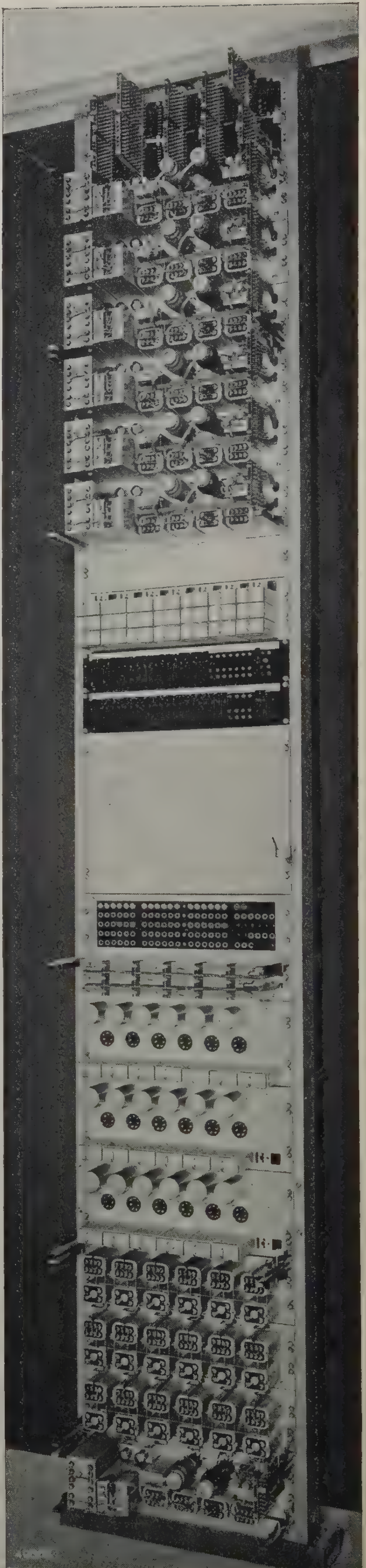

Fig. 11. Bay with signalling receivers and relays of a carrier installation for 17 channels (11 of the 18 receivers are mounted on the back of the bay; one receiver serves as reserve).

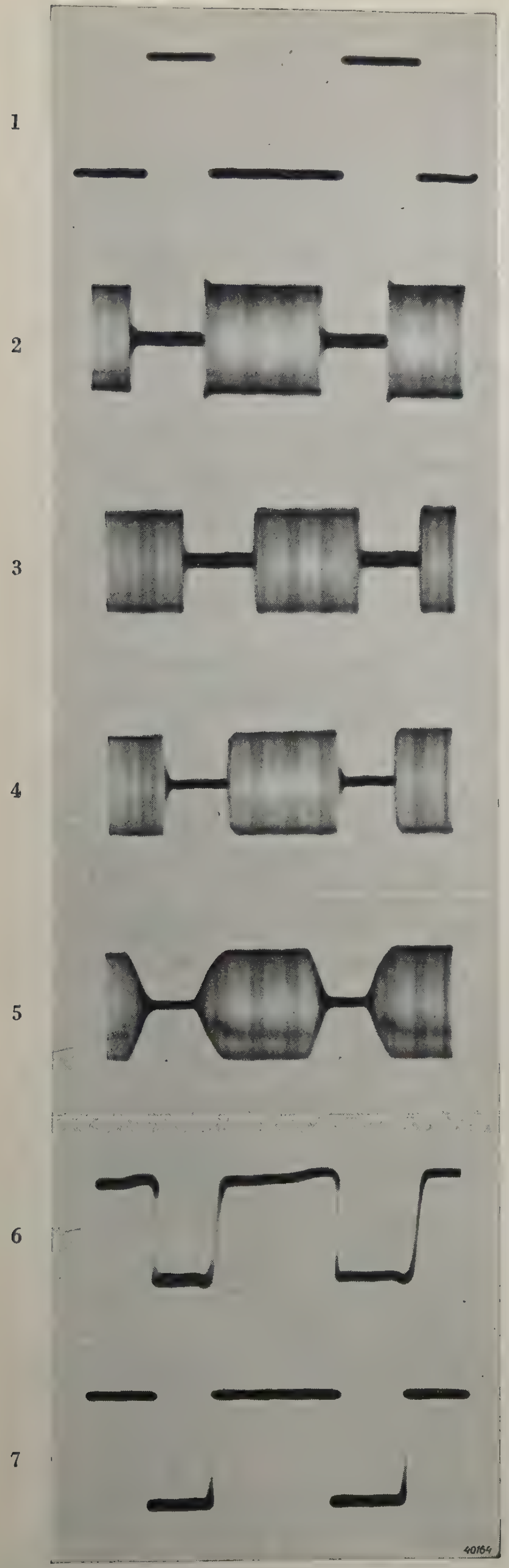

Fig. 12. Oscillograms of the dialling impulses recorded at points 1-7 of the diagram of fig. 6.

nal *1* the relay will react at C and release at D; the impulse, passed on by the relay C_2, is thus considerably shorter (length CD) than the original impulse. With the stronger signal *2* the relay operates from E to F, which is equal in length to the time AB. In the case of the very strong signal *3*, the relay operates from G to H, and the impulse passed on is thus longer than the original one.

If the signal intensity received were always the same, then, by a suitable choice of the bias V_0, it could be ensured, that the impulses, passed on, have the correct length. Actually, however, one must count on signals of different intensities. The cause of this lies for a large part in the dependence on temperature of the damping of the transmitting and receiving band filters. Temperature changes cause the values of the capacities and self-inductions in the filter to vary somewhat, so that the whole damping characteristic is shifted slightly in frequency. Since the carrier wave lies just in the region, where the damping curve mounts quite steeply, a slight shift in the damping curve quickly causes a considerable change in the damping for the carrier wave.

By means of a simple device, it is possible to neutralize almost completely this distortion caused by the variation in intensity. Provision is made that the weakest signal occurring has the shape of curve *2*, with which no grid currents yet occur. With larger signals, like that of curve *3*, grid current begins to flow. By now including in the grid circuit, as may be seen in fig. 8, a grid condenser C and a leakage resistance R of suitable value, the grid current is made to increase the negative bias, by such an amount (V_0' in fig. 13), that the operation and release of C_2 takes place at points I and K (instead of G and H), which with the signal in the form of curve *3* have exactly the desired time interval. At a different signal intensity the correction will not be quite exact, but a good approximation is obtained in the whole practically important range of variation of the signal intensity.

In the sixth oscillogram of fig. 12, the variation of the anode current of the detector valve is shown, in the seventh oscillogram, the impulses set up by the contact of the relay C_2. It is seen that here, apart from the inversion, which is cancelled in the relay group, a faithful image of the original impulses is obtained.

In addition to the distortion by the various filters discussed here, there is still another sort of distortion, requiring special measures. Let us return to the diagram of fig. 6. The relay C_1, that puts the carrier wave on the line, is controlled, *via* the relay group *Re*, by the D.C. impulses arriving at *a*. The direct current is now passed on to the modulator by the transformers situated in the four-wire termination *V*. The D.C. impulses, however, are built up not only from the direct current, but also from a series of A.C. components, which are allowed to pass and which are modulated on the carrier wave in the modulator, like the ordinary speech frequencies. This takes place practically without any retardation, calculated from *a* to the output of the modulator. The relays, however, which transmit the signals proper, work with a certain lag. The relay in the

6) See the article referred to in footnote 4).

relay group *Re*, for instance, needs 0.01 sec to react, while C_1, an especially high-speed relay of special construction [7]), still needs 0.002 sec. Therefore, the A.C. components of the D.C. impulses reach the signalling receiver 0.012 sec before the signal proper; in as far as the frequencies of these components lie below about 300 c/sec, they can pass the filter in the signalling receiver without too great attenuation and cause relay C_2 to operate. As a result, a short surge precedes the impulse proper and the grid voltage of the detector valve may become so strongly negative, that the succeeding impulse is not received well.

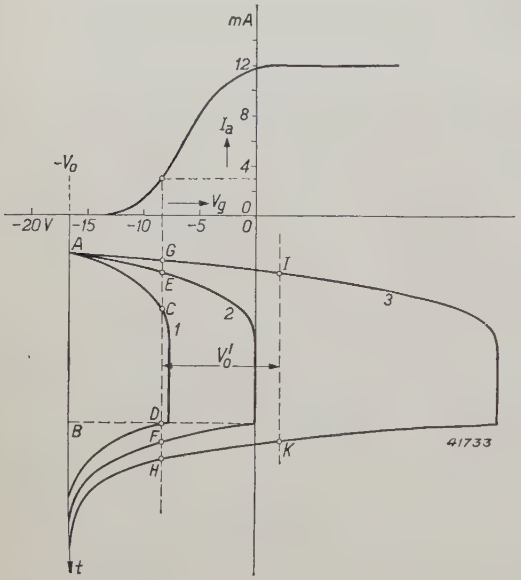

Fig. 13. I_a-V_g diagram of the detector valve in the signalling receiver. *1*, *2*, *3* behaviour with time of the grid A.C. voltage amplitude at three different intensities of the incoming dialling impulses.

The effect is counteracted, to some extent, by the limiter connected behind the four-wire termination, cutting off all peak voltages above a certain value (level for example 6 mW). This is not enough however. In order to dissipate the effect entirely, another filter is connected here in the speech channel, which causes a reasonable attenuation, namely at least 35 dB for frequencies below 300 c/sec (*i.e.* below the frequency band necessary for speech). The damping curve of this high-pass filter is shown as a broken line in fig. 9 for the modulated vibrations at the input of the 8 kc/sec filter in the signalling receiver.

The high-pass filter is also important for rendering the lowest frequencies in the speech currents absolutely harmless, and also to prevent any other signals, such as dialling tone or ringing tone, sent over the speech channel and also having components in the low-frequency region from acting upon the signalling receiver.

Finally a few words must be added about the intensity of the signals. The higher the intensity, the less the trouble experienced from all kinds of interferences, such as the carrier leak of the modulators. On the other hand, the signalling intensity may not be so high that the amplifiers common to all channels are overloaded. When only impulses are transmitted, which have a very short duration compared with the total duration of the call, this danger is only slight. Thus in the case of the system for carrier telephony with 17 channels, formerly developed by Philips, a level can be used for signalling, which corresponds to 1·5 mW, measured at the input of the four-wire termination. This corresponds, approximately, to the average level of the conversation itself and lies 30 dB, or more, above the possible carrier leak. If, however, it is desired to signal continuously and not with impulses, either the signal intensity must be chosen considerably lower or the amplifiers must have larger dimensions. It will depend upon the circumstances, whether the above-mentioned advantages of continuous signalling carry more weight than these disadvantages.

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[7]) This is done also because of the distortion. Of itself an operating time and a releasing time of for instance 0.01 sec. is no objection, since it means only a slight retardation of all the impulses. If, however, the operating time and the releasing time of the relay C_1 are not exactly the same, the impulses become too long or too short. The unavoidable differences between the two times, taken absolutely, will be smaller, the shorter the two are taken.

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by Th. J. J. A. MANDERS.

615.831.7:621.384

The therapeutic action of infra-red rays lies mainly in the temperature increase in the irradiated tissue. It is important, that the radiation should penetrate into the body as deeply as possible.

A study has therefore been made of the spectral distribution of the radiation necessary, in order that, with the given reflection and absorption of the skin, this requirement may be satisfied. An irradiator is then described, which emits rays with a spectral distribution, corresponding quite satisfactorily with the optimum distribution.

For several years already the therapeutic action of infra-red rays has been a subject of interest to the medical profession. At first, little was known about the way, in which the rays act, and very diverse sources of radiation were employed. On the one hand neon tubes were used, which emit the greater part of their radiation in the long-wave visible region; on the other hand electric heaters were used, whose radiation is mainly far in the infra-red. Research in recent years, however, has shown, that the curative effect of the radiation is, for the most part, to be accounted for by the heating of the tissue. From this it follows, that the wave length of the radiation is not of primary importance, the heating effect being entirely determined by the amount of radiant energy absorbed. But the spectral distribution of the radiation is by no means unimportant. From the investigations referred to, it has also been found, that the most favourable effect is obtained, when the radiation penetrates, as deeply as possible, into the tissues. A radiation must therefore be used, which is absorbed as little as possible by the skin.

Further it is obvious, that the rays emitted should be reflected as little as possible by the skin, thereby increasing the efficiency of the irradiation. By these requirements the spectral distribution of the radiation, to be used, is to a large extent fixed.

In this article we will describe the "Infraphil" irradiator, an apparatus of such simple construction, that under a doctor's directions, it can be used by laymen, for instance for alleviating rheumatic pains, for the treatmant of inflammations, etc. By a suitable construction of the radiator proper, it has been ensured, that a high percentage of the energy emitted, is converted into heat in the deeper-lying layers of the tissue.

The properties of the skin

In the foregoing it has been shown, that the properties of the skin almost completely determine the spectral distribution of the radiation. Those properties will therefore be examined in some detail.

Reflection

The reflectivity of the skin has been determined by various investigators, among whom are Schultze, Bode, Hardy and Muschenheim and Büttner. It has been found, that the reflectivity for infra-red rays, contrary to that for visible light, depends little on the intensity of the pigmentation of the skin. The reflection has a maximum between 0.6 and 0.7 μ and decreases rapidly towards the infra-red. In *fig. 1* the variation of the reflectivity is shown for a moderately pigmented skin, as found by the investigators mentioned.

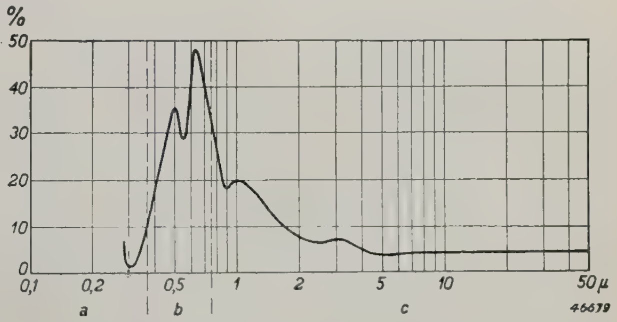

Fig. 1. Reflectivity of the skin as a function of the wave length in μ. *a* Ultra-violet region, *b* Visible region, *c* Infra-red region.

Translucency of the skin

As already noted, the red and especially the infra-red rays are relatively little reflected. The greater part of this radiation, therefore, penetrates into the skin. The depth of penetration will depend upon the scattering and absorption by the skin.

Little is known of the scattering power of the skin. Plotnikow found, that it is dependent on the wave length of the radiation and further on the thickness of the different skin layers. The investigators, mentioned below, have attempted to take this into account in the determination of the absorption.

The absorption of the skin, for different wave lengths, has been measured by various investigators, among whom **Hardy** and **Muschenheim** and **Henschke**. Their results are reproduced in *fig. 2*, from which it may be seen that, especially with a rather thick skin, practically only the wave length region from 0.6 to 1.4 μ is to be considered. The maximum translucency lies at about 1.2 μ. The shape of the translucency curve can be explained satisfactorily from the corresponding curves for the substances mainly responsible for the absorption in the skin, namely water and oxyhaemoglobin. Its shape above 1.2 μ especially is mainly determined by the water, while the sharp limit at 0.5 μ is to be ascribed to the action of the oxyhaemoglobin.

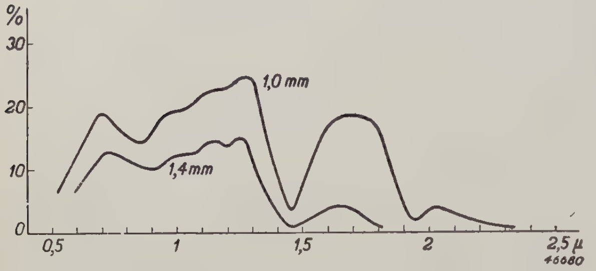

Fig. 2. Translucency of the skin as a function of the wave length in μ, for a skin thickness of 1.0 and 1.4 mm respectively.

Furthermore **Bachem** has ascertained, that the region of greatest translucency for the more deeply lying parts of the skin is shifted towards long wave lengths. This phenomenon too is to be ascribed to the oxyhaemoglobin. The more deeply lying parts of the skin (*i.e.* the corium) are richer in blood than the epidermis and therefore contain relatively more oxyhaemoglobin.

For the rest no exaggerated ideas of the depth, to which the radiation penetrates, can be entertained, even for the most favourable wave lengths. From experiments by **Henschke**, **Heald** and **Hofmann** it has been found, that the intensity of radiation, in the region between 0.7 and 1.1 μ, is reduced to 0.1 percent of the original intensity, already at a depth of 2 cm. This is confirmed by measurements of the temperature distribution in the skin by **Henschke**. His results from experiments carried out with radiation in the region of 0.6—1.3 μ are reproduced in *fig. 3*, from which it may be seen, that considerable increases of temperature may occur at the surface of the skin, whereas at depths greater than 1 cm practically no increase can be detected.

From the foregoing it may be deduced, that a radiation in the wave-length region of 0.6 μ—1.4 μ is most suitable for irradiation. Radiation, in the region outside this interval, must be suppressed as much as possible, since it is mainly absorbed in the outer layers of the skin and heats it intensely, thereby limiting the amount of energy that can be irradiated on the skin per cm^2. This maximum energy per unit of area, the so-called loading capacity, is determined by the pain limit. If the intensity of the radiation is too high, a strong heating effect is first experienced, then an irritation, which finally becomes an intolerable pain. With all irradiations, therefore, there is a limit to the intensity that can be tolerated for a long time. This limit depends naturally on the spectral composition of the rays emitted. In choosing the dimensions of the irradiation apparatus, to be described farther on, it is therefore important, as **Henschke** found, that the limit in question should vary but little (about 5%) for different people. **Van Wijk**[1]) determined the loading capacity for heat irradiators of different temperatures mounted in glass bulbs (wall thickness about 1 mm). His results are shown in *fig. 4*. It is found, that the loading capacity increases considerably with rising temperature of the radiating body.

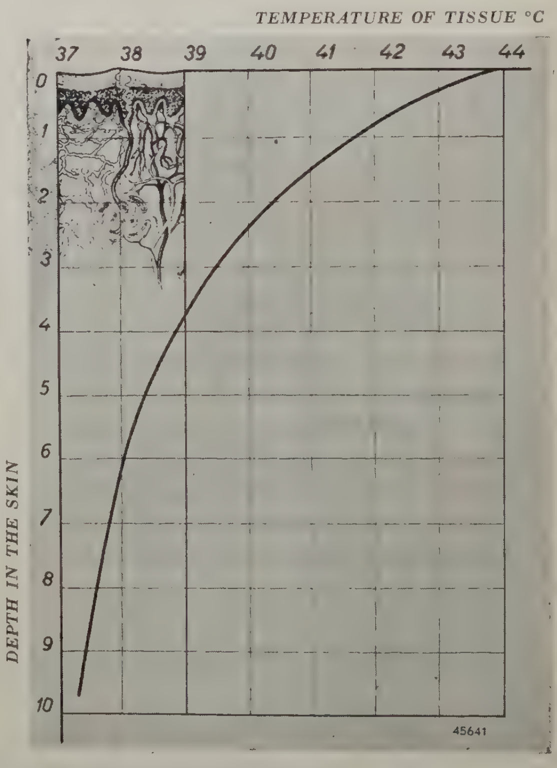

Fig. 3. Temperature of the tissue at different depths in the skin, when the surface of the skin is kept at 44 °C by irradiation (in the region between 0.6 and 1.3 μ).

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[1]) Philips techn. Rev. **6**, 202, 1941.

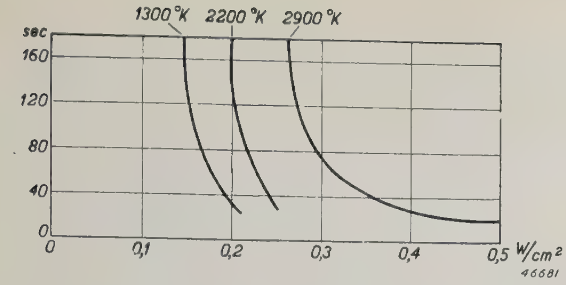


Fig. 4. Time, during which an irradiation can be tolerated, as a function of the intensity of irradiation for different temperatures of the incandescent body of the irradiator. The time is measured in seconds, the irradiation intensity in W/cm² and the temperature of the incandescent body in degrees K.

Physical properties of the apparatus

From the foregoing, it has become evident, that an apparatus for irradiation with infra-red rays must satisfy the requirement, that the largest possible part of the rays should lie in the wavelength region 0.6 μ—1.4 μ. Confining ourselves to heat irradiators, the maximum of the radiation curve should therefore lie in this interval, and since these curves fall off much more rapidly towards the short wave side than towards the other side, the maximum must lie quite close to 0.6 μ. With the help of Wien's displacement law, it may already be deduced that the temperature of the irradiator has to be very high. If we express the wave-length λ in μ and the temperature T in degrees K, Wien's law is as follows:

$$\lambda_{max} \cdot T = 2880.$$

For $\lambda_{max} = 6$ μ, it follows, that $T = 2880$ °K.

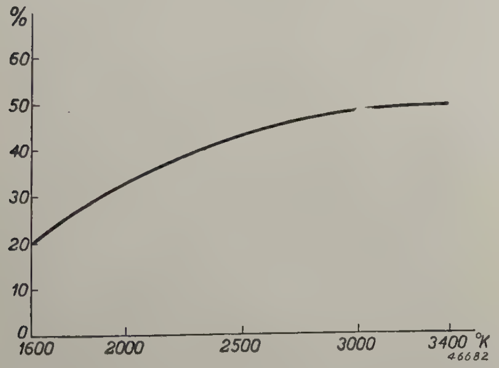


Fig. 5. The part of the total radiation of a tungsten coil, which falls in the region 0.7 μ—1.4, μ at different temperatures expressed in degrees K.

In *fig.* 5 the part of the energy from a tungsten coil, which is emitted in the region in question, is indicated for different temperatures. It may be seen that, in good agreement with the above, the part, falling in the region from 0.6 μ to 1.4 μ, increases up to about 3400 °K.

In the case of the "Infraphil" apparatus, a tungsten coil is actually used, which, when in operation, consumes 150 W and reaches a temperature of 2800 °K. Although this is about the same temperature as is reached in an ordinary electric lamp of the same power, it is impossible to go much higher, because the tungsten would then evaporate at such a rate, that the lifetime of the irradiator would become far too short, to be of any practical use. At the temperature mentioned, therefore, the maximum yield of radiation in the region 0.6 μ to 1.4 μ is not obtained. Since, however, as is shown in figs. 1 and 2, the shortwave radiation in that region is more strongly absorbed by the skin, and especially more strongly reflected, a very satisfactory result is, nevertheless, ultimately obtained.

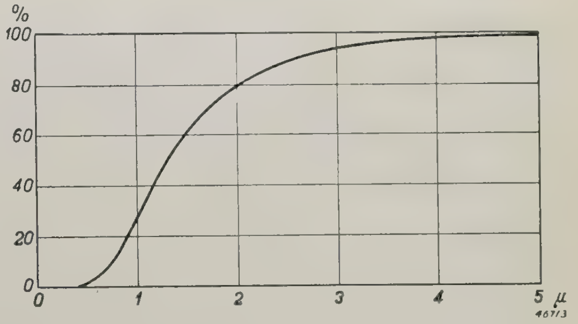


Fig. 6. Spectral distribution of the radiation of a tungsten coil at 2800 °K, represented in accumulated form.

In *fig.* 6 the spectral distribution is given of the radiation of a tungsten coil at a temperature of 2800 °K (curve A). The diagram is given in an accumulated form, so that it is possible, to read off directly, what part of the radiation is emitted in the region from zero to a given wave length (and by subtraction, therefore, also the part in a region between any two wave lengths; with a non-accumulated distribution curve these percentages would have to be determined, for instance, by planimetry).

As tungsten readily oxidizes, especially at high temperatures, the incandescent body has to be fused into a glass bulb. The socket end of this bulb has the shape of a paraboloid and is mirrored on the inside, thus concentrating the energy. The greatest diameter of the bulb is 125 mm (see *fig.* 7).

The internally deposited aluminium mirror offers many advantages over an externally applied reflector. In the first place the rays have to pass only once through the wall of the bulb, whereas with an external reflector at least the central portion of the beam has to pass through the glass three times. The absorption is therefore less. Further, the internal mirror is less exposed to damage and is protec-

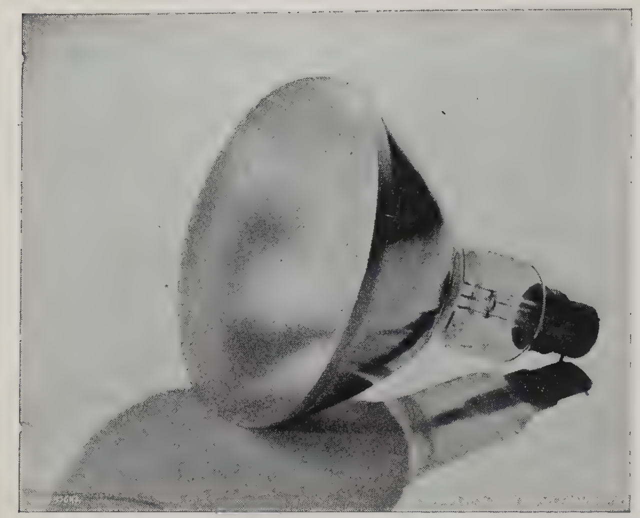


Fig. 7. The radiator of the "Infraphil" apparatus, showing the frosted front and the mirrored back of the bulb.

ted against contamination; finally it occupies no extra space.

The mirror is applied by evaporation of aluminium on the inside of the bulb. In *fig. 8* the reflection of aluminium, deposited by evaporation, is given as a function of the wavelength. In the whole region in question, aluminium is found to be a good reflector, so that the mirror causes practically no changes in the spectral composition of the ray beam emitted.

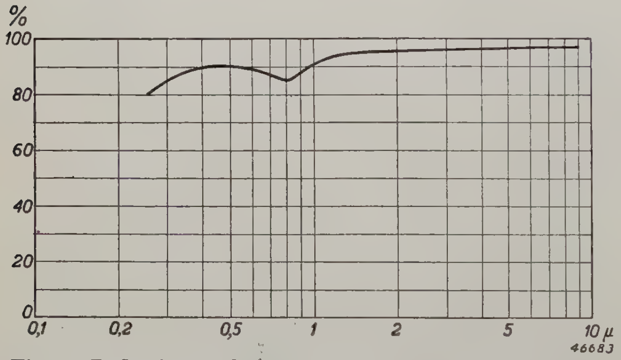


Fig. 8. Reflectivity of aluminium deposited by evaporation for different wave lengths (in μ).

A second factor of influence on the radiation emitted through the bulb is the translucency of the glass. This is represented graphically in *fig. 9*. The transmission is very good in the region that counts. Only at 2.5 μ does absorption clearly begin to occur. This, however, is an advantage, because part of the undesired radiation with a wave length greater than 1.4 μ is thereby removed.

After what has been stated in the foregoing, it will not be surprizing that in the region with which we are concerned, the spectral distribution of the beam leaving the bulb differs little from that of the radiation from the filament, shown in fig. 7. Notwithstanding the above-mentioned absorption effect, a not inconsiderable part of the radiation emitted has a wave length greater than 1.4 μ. By applying a water filter (see the article by van Wijk already referred to) this radiation could practically be eliminated. It would thereby be possible to increase the loading capacity from 0.27 W/cm² (see fig. 4) to about 0.45 W/cm². For an apparatus mainly intended to be used by laymen, however, this would be too complicated and also make it too expensive.

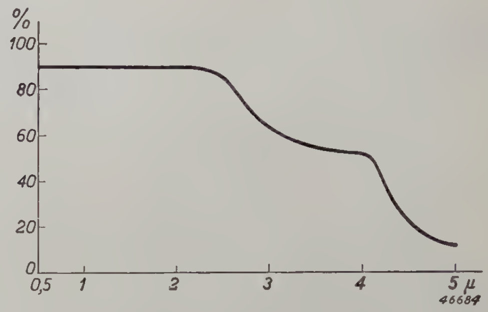


Fig. 9. Translucency of calcium glass for different wave lengths (in μ). Thickness of glass 1 mm.

The front of the bulb is frosted, in order to render the intensity at the centre of the beam equal at all points. If this were not done, local irradiation maxima would occur on the part of the skin irradiated. This has an unfavourable effect, because the total radiation, that can be tolerated, is finally determined by the loading capacity of the most intensely irradiated area of the skin.

Finally in *fig. 10*, the irradiation intensity is shown on a plane perpendicular to the axis of the irradiator, at different distances from the axis.

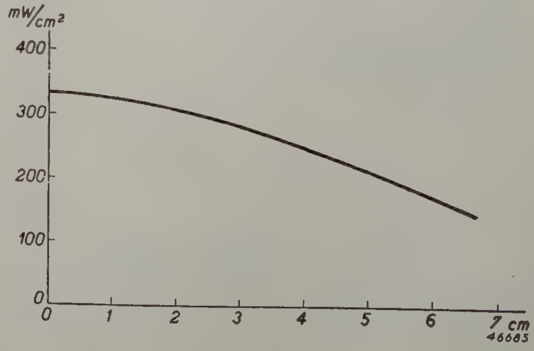


Fig. 10. Intensity of the irradiation as a function of the distance from the centre of the beam, measured in a flat plane perpendicular to the axis at 25 cm distance from the front of the irradiator.

Details of the apparatus

In *fig. 11* the complete "Infraphil" apparatus is

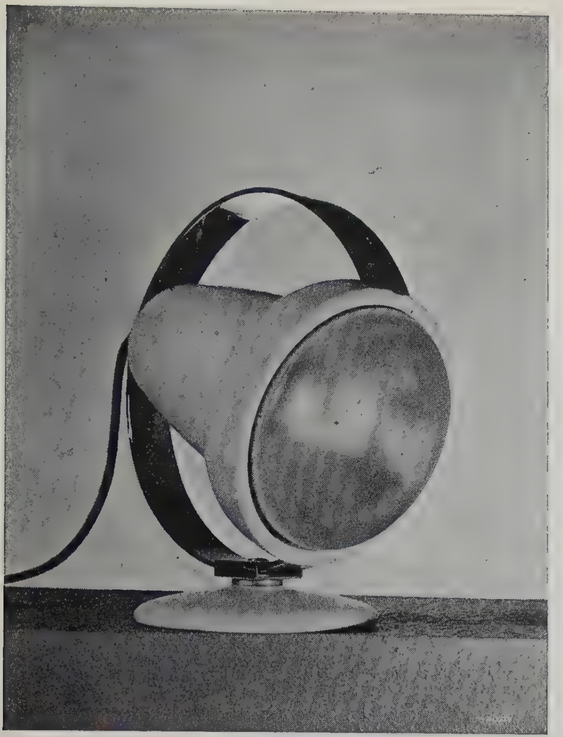


Fig. 11. The complete "Infraphil" apparatus. The bracket, in which the irradiator is hung, can be translated and rotated with respect to the base. The irradiator can therefore be placed in any desired position.

shown. The irradiator, already discussed, is contained in a metal housing held in a bracket.

The bracket is made movable by means of a grooved clamp, so that the beam is adjustable within the plane of the bracket. Moreover, the clamp can be rotated about the axis of the base, so that when the apparatus is hung on the wall — an eyelet is provided for this purpose underneath the base — the beam can be adjusted in every desired direction. For use by a medical practitioner, the apparatus is supplied with a stand, providings till wider possibilities of adjustment (*fig. 12*). Here the radiator with bracket is attached to a tube, instead of to the base. This tube passes through a clamp, in which it can be rotated, and also moved in a horizontal direction. The clamp itself can, moreover, be moved along a vertical tube and rotated about it. A switch is mounted between bracket and tube.

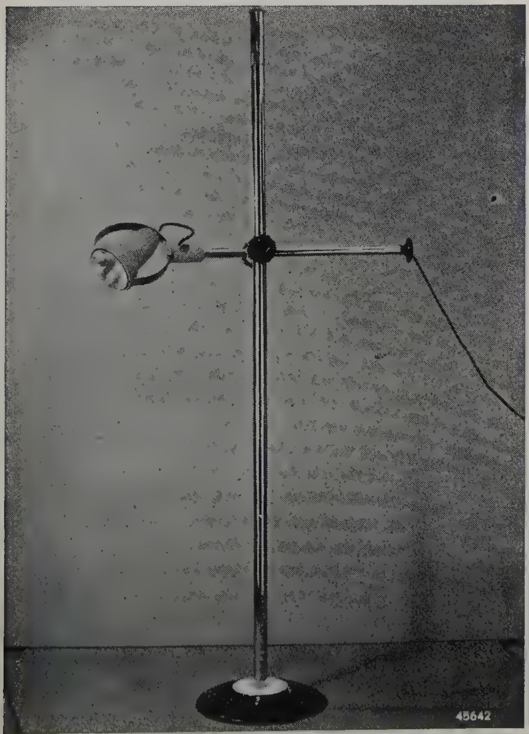


Fig. 12. The "Infraphil" apparatus with stand.

In certain cases it is desirable to be able to administer very local irradiation. For this purpose, a number of localizers have been designed (*fig. 13*), which can be attached to the apparatus very simply, with the help of a ring. The apparatus with a localizer is shown in *fig. 14*.

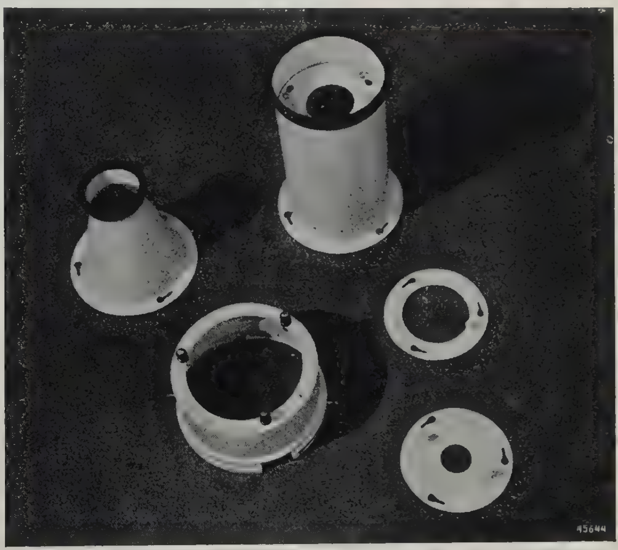


Fig. 13. Various forms of localizers, designed for very local irradiation. On the left in the foreground, is the ring, with which the localizers are attached to the housing.

Applying the apparatus

It can be taken that infra-red rays have no injurious effect upon the eyes, during the short time, that irradiation is usually applied. In fact, the visible radiation is so intense, that one automatically shuts the eyes, if the beam falls upon them. Nevertheless, in the latter case it is desirable to protect the eyes, as much as possible. Care must be taken, when using goggles, because they may absorb so much heat that, they may burn the skin, where the frame touches it. Readily inflammable objects, such as combs, etc., must be kept out of the field of radiation.

In general, the intensity of irradiation should be as high as possible. The distance from the skin must therefore be as short as possible, but not so short as to be painful. The heat should be comfortably bearable. From this, it follows, that care must be taken, when irradiating places which for some reason or other have become insensitive, for then there is no feeling of pain to give warning, if the beam becomes too intensive, and burns may result.

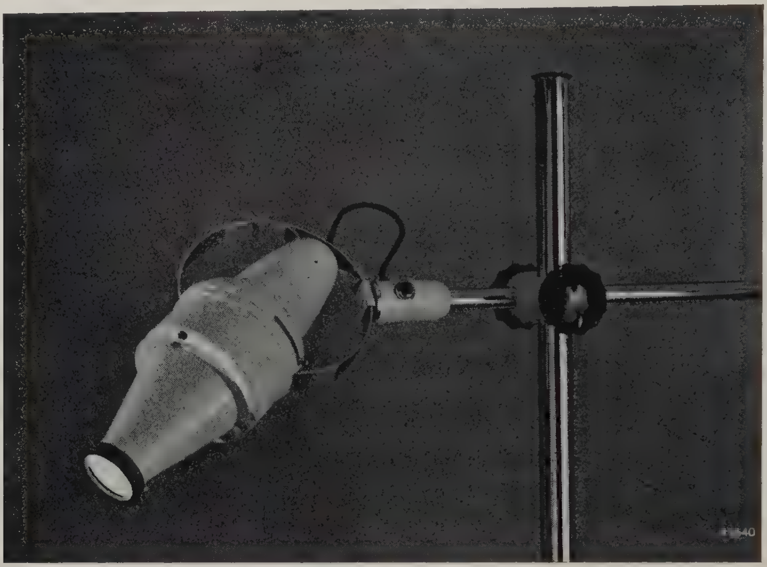


Fig. 14. The "Infraphil" apparatus on a stand, with a localizer in place.

ELIMINATING SCATTERED RADIATION IN MEDICAL X-RAY PHOTOGRAPHS

by W. J. OOSTERKAMP.

778.33:535.361.2

The scattered radiation, occurring in the diagnostical X-ray examination of the human body, produces a uniform secondary exposure of the X-ray film (or secondary illumination of the fluoroscope), thereby considerably reducing the sharpness of the contrasts. Various methods have therefore been developed, to eliminate scattered radiation or to reduce its effect on the film or screen. The criterion for the value of each method is the "selectivity", *i.e.* the ratio between the attenuation factor for the scattered rays and that for the primary radiation, producing the desired X-ray shadow picture. The present article first gives a survey of the usual methods of eliminating scattered rays and then proceeds to deal in more detail with one of the most important of them, the so-called Potter-Bucky diaphragm. Various forms of such diaphragms are compared as to selectivity and other properties, from which indications are deduced for their most efficient construction. In most of the methods of counteracting scattered radiation, there is some disadvantage or other, that has to be taken into the bargain, such as a distortion, further lack of definition, etc. The doctor must therefore decide for himself, which method or combination of methods is most suitable for a certain examination.

Introduction

The familiar shadow image of the internal organs and skeletal parts, obtained in X-ray photography (or fluoroscopy) of the human body is brought about by the difference in degree of attenuation of the X-rays, while passing through the various parts of the body. According as the intensity of the primary radiation, propagated rectilinearly from the focus of the X-ray tube, varies from place to place, so certain contrasts are formed in the blackening of the X-ray film.

Actually, however, the contrasts are always less defined, than would be expected from the above. The reason for this lies in the scattering of X-rays. The attenuation of the primary X-rays in matter is caused partly by absorption and partly by scattering, *i.e.* a change in the direction of the rays (accompanied by a certain loss of energy, which, however, with the tube voltage used in X-ray diagnostics is only slight). Owing to the fact, that the scattered rays from every particle of the body exposed to the primary radiation travel in relatively random directions, they cause a more or less diffuse exposure of the film, which leads to fogging and, consequently, diminishes the contrasts.

It will be seen from the following, that this effect is very important in X-ray photographing of the human body. In the case of elements with a high atomic weight, the attenuation of the X-rays is mainly due to absorption, for example in the bones, which consist for a large part of calcareous matter (with the relatively heavy element calcium). The other human tissues, however, are composed almost entirely of elements with a low atomic weight (hydrogen, carbon, nitrogen, oxygen), and in them, with the usual tube voltages employed, the attenuation due to scattering is of the same order of magnitude, as that due to absorption. Since in diagnostics, it is in many cases a question of distinguishing very slight contrasts in the X-ray picture, various methods have been developed for neutralizing or eliminating the scattered rays. These methods will be described in this article and as far as possible considered quantitatively. The striking improvement in contrast, sometimes obtained by counteracting scattered rays, is demonstrated by *fig. 1*, in which two X-ray photographs of the pelvic region are reproduced. The first was taken without any special measures for the elimination of scattered rays, whereas, in the second a large part of the scattered radiation was intercepted by means of a so-called Potter-Bucky diaphragm.

We shall begin with a somewhat more detailed consideration of the influence of scattered rays on the formation of the X-ray picture.

Influence of scattered rays on the X-ray picture

Radiation contrast

We assume, for the sake of simplicity, that the object irradiated is of a homogeneous composition with the exception of a small part M, in which the attenuation of the primary rays is slightly greater, than in the remaining part (see *fig. 2*).

This part M then appears on the negative as a spot M', which is slightly lighter than the surroundings. However, M' is struck not only by the direct rays but also by scattered rays, coming from all the points of the object irradiated. The intensity of these scattered rays is practically the same, all over the film.

What effect does this have on the contrast? To be precise, we must here distinguish between radiation contrast, *i.e.* the relative difference in radiation intensity, and the resultant photographic contrast, *i.e.* the relative difference in blackening of the film. As to the first, we assume, that in the example mentioned, the primary radiation has the intensity I_p all over the film, except for the spot M', where the intensity is I_p—ΔI_p. The radiation contrast K_p between M' and the rest of the film, which would be obtained, if there were no scattered radiation, then amounts to:

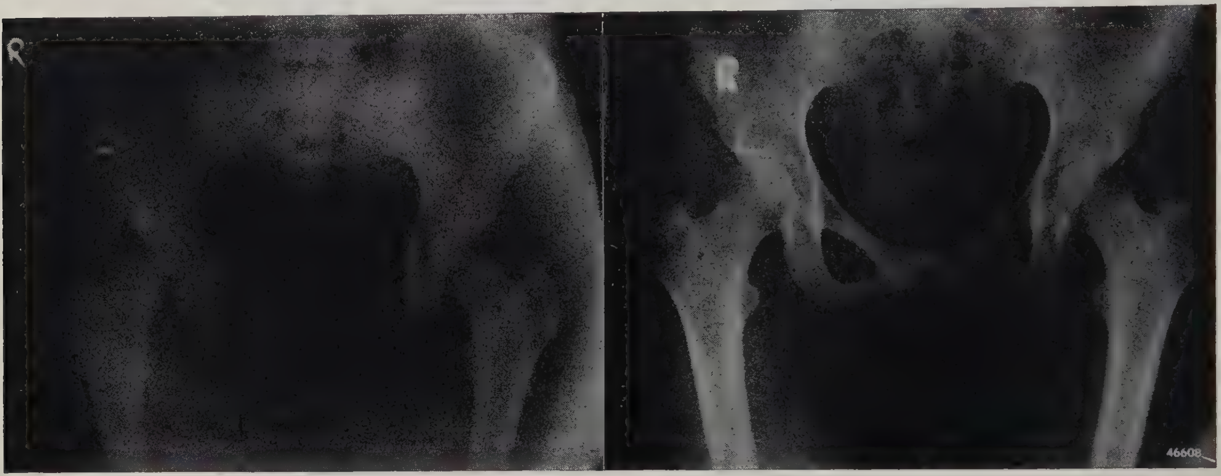
$$K_p = \frac{I_p-(I_p-\Delta I_p)}{I_p} = \frac{\Delta I_p}{I_p}\,.$$

Actually, there is a scattered radiation all over the film, the intensity of which we shall call I_s. As a consequence, the total intensity on M' is I_p—$\Delta I_p + I_s$, and on the rest of the film $I_p + I_s$. Thus, under the influence of the scattered rays, the radiation contrast is changed and becomes:

$$K_s = \frac{(I_p+I_s)-(I_p-\Delta I_p+I_s)}{I_p+I_s} = \frac{\Delta I_p}{I_p+I_s}\,.$$

It is thus clear, that the radiation contrast is diminished by the scattered radiation, the decrease being in the ratio of:

$$\frac{K_p}{K_s} = \frac{I_p+I_s}{I_p}\,.$$



a b

Fig. 1. X-ray photograph of the pelvic region, *a*) taken without measures to eliminate scattered radiation, *b*) taken with a diaphragm to reduce the scattered radiation (Potter-Bucky diaphragm).

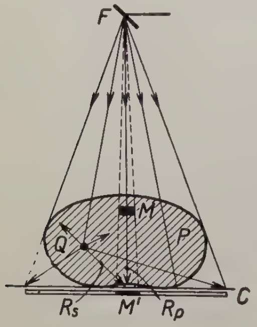


Fig. 2. In the body P there is an inhomogeniety M. This causes a somewhat greater attenuation of the primary X-rays R_p, coming from the focus F, and thus throws a shadow M' on the film C. Scattered rays R_s, which originate at every point Q of the body P, also strike the film at M'.

For the sake of orientation, it may be stated that, in a photograph of the lung, the intensity of the scattered radiation is approximately equal to that of the primary radiation, while, in photographs of the abdominal organs, I_s may be three or four times I_p, or even more. In lung photographs therefore $K_p/K_s = 2$, thus the radiation contrast is reduced to one half by the scattered radiation, and in abdomen photographs $K_p/K_s = 4$ or 5, the contrast thus being reduced to 1/4 or 1/5 of the value, which would be obtained without scattered radiation.

Photographic contrast

With the total radiation $I_p + I_s$ acting upon the photographic film, one could imagine the situation being such, that the film is first exposed, for the prescribed time, only with the direct radiation I_p, which forms the picture, and then re-exposed once more for the same time, without the patient, to a uniform radiation I_s/I_p times as intense. The disastrous effect of such a uniform after-exposure is obvious. Upon closer examination, however, it is seen, that in reality the situation is more complicated. The reduction in contrast on the film, due to the scattered rays, will only be of the same order as that of the radiation contrast, when one is working on the linear part of the blackening curve, both with and without scattered rays. This condition will certainly not be satisfied, if by applying some means or other the scattered radiation were entirely eliminated and a photograph were then made with the same exposure time, as was first used with scattered radiation present.

Especially, in the case of moving objects (heart, lungs, etc), having regard to the lack of definition of the movement, the exposure time is chosen as short as is compatible with the requirement of sufficient blackening density, and if that density is only just sufficient with scattered radiation, it will certainly be insufficient without it. Since this means, that one works in a less favourable part of the blackening density curve and consequently with a given radiation contrast, one obtains a smaller photographic contrast, it is to be concluded that in an ordinary X-ray photograph the uniformly distributed exposure by the scattered rays does indeed spoil the radiation contrast, but in the photographic contrast partially makes up for that effect, by shifting all the amounts of radiation to a more favourable part of the density curve.

This need not, however, prevent us from eliminating the scattered rays, because, in order to reach the most favourable part of the density curve, there are other means available, which have no such prohibitive drawbacks. In principle, the essence of these methods lies in an increasing of the quantity of the primary radiation itself, so as to obtain the original blackening.

Increasing the quantity of primary radiation

The quantity of primary radiation can be most simply increased by lengthening the exposure time. If the scattered radiation I_s is entirely eliminated and the intensity I_p of the primary radiation remains unchanged, the total radiation is decreased by a factor $I_p/(I_p + I_s)$. In order, therefore, to obtain the same blackening density, the exposure time must be increased by the factor [1]).

In an abdomen photograph, therefore, the exposure time would have to be four to five times as long.

Actually, in almost all methods of eliminating scattered radiation, on the one hand also I_p is decreased and on the other I_s is not reduced exactly to zero. If we denote the intensities, to which the primary and the scattered radiations are reduced, by I_p' and I_s' respectively, the required factor of increase of exposure time becomes:

$$B = \frac{I_p' + I_s'}{I_p + I_s}.$$

When so-called Potter-Bucky diaphragms are used to eliminate scattered radiation, which we shall presently discuss in detail, B is called the "Bucky factor".

We have already alluded to the fact that, increasing the exposure time in the case of moving objects increases the lack of definition, due to the movement. It is possible to retain the original exposure time and instead: 1) increase the intensity of the primary radiation by expanding the area of the focus of the X-ray tube, or 2) use more sensitive intensifying screens, at the front and back of the X-ray film, in order to convert the primary X-radiation into a form of radiation more favourable for the blackening. By the first method, the geometrical blurring (width of the half-shadow caused by the finite focus width) is increased, whilst the second is accompanied by a greater blurring due to the screens, since more sensitive screens give in general a poorer definition [2]). Thus in any case part of the definition must be sacrificed. The best course to follow is determined by the so-called uniformity condition, *i.e.* the three components of the blurring (that caused by the moving of the object, that due to the screen and the geometrical blurring) should be approximately equal.

There is also another possibility of compensating for the loss of intensity, caused by eliminating the scattered radiation, namely by increasing the voltage on the X-ray tube, thereby obtaining a more intensive but, also particularly, a harder radiation, which is less attenuated in the patient's body, so that much more radiation reaches the film. Although it is true that, in consequence of this reduced attenuation of the primary rays, a somewhat reduced radiation contrast is obtained, usually the gain in contrast for the total radiation, resulting from the removal of the scattered rays, more than compensates for that.

Review of the methods of eliminating scattered radiation

When discussing the different methods of counteracting scattered radiation and comparing them with each other, we must have a measure, by which to express the value of a method quantitatively. The attenuation factor for the scattered rays, which we shall call S ($S = I_s'/I_s$), is not suitable for the purpose, because if S is small, but at the same time the primary radiation is also very much attenuated (attenuation factor $P = I_p'/I_p$), the method has little or no value. The requirement is rather that the scattered rays should be much more strongly attenuated than the primary radiation, in other words, that the method should have a selective attenuating effect on the scattered rays. The value of a method can therefore be judged according to the ratio $P/S = \Sigma$, the so-called selectivity, which was first introduced by de Waard[3]). The larger Σ, the more closely the ultimate object is approached. At the same time, however, there is the condition, that P itself may not be very much smaller than unity, since a large loss of direct radiation necessitates a further increase of the exposure time (in addition to the already mentioned increase necessary as a result of the elimination of the scattered radiation).

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[1]) If we assume, for the sake of simplicity, that the blackening is determined entirely by the quantity of radiation. This is a slight deviation from the actual fact. (Schwarzschild effect.)

[2]) For an explanation of this see for example Philips Techn. Rev. 5, 266, 1940. It is in any case assumed, that the highest possible value permissible in connection with the focus temperature is chosen for the tube voltage, which is one of the factors determining the X-ray intensity.

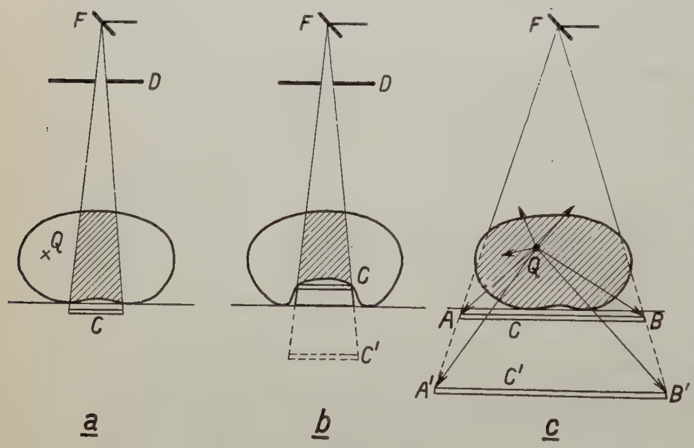

Fig. 3. Three simple methods of limiting the scattered rays.
a) Reducing the size of the field by means of a diaphragm *D*. There are then many points *Q* in the body, which contribute less to the scattered radiation.
b) Pushing aside as much body tissue as possible by compression. The method can best be combined with that of *c*).
c) Increasing the distance between patient and film. In the position *C* of the film it is struck by all the scattered radiation from *Q* within the solid angle *AQB*; in position *C'* only by the scattered radiation within the angle *A'QB'*.

Apart from the selectivity, there are also other factors, which are not so easily expressed in numbers and which are likewise of importance in estimating the usefulness of a method for counteracting the scattered radiation. These factors will be dealt with, as they arise in the discussion of the different methods.

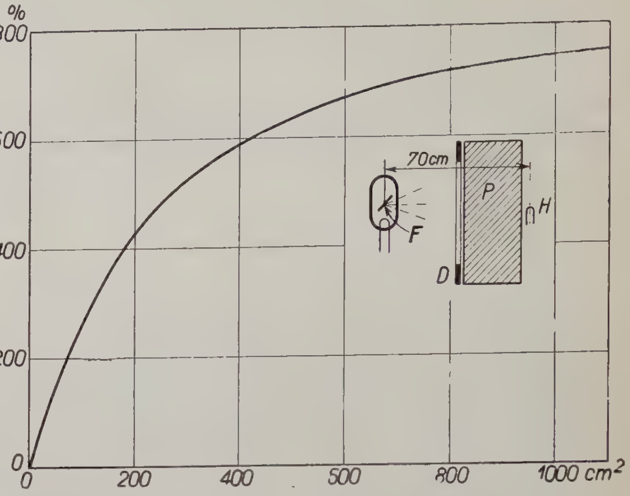

Fig. 4. Influence of the size of the field on the scattered radiation. With the help of a phantom *P*, consisting of "Philite", with a total thickness of 16 cm and intermediate layers of air totally 5 cm in thickness, a stomach examination was imitated, while the intensity of the scattered radiation was determined with a Hammer thimble dosemeter *H* for different openings of the square diaphragm *D*, at 100 kV tube voltage (DC voltage with a ripple of 30 kV) and 30 mA tube current. The scattered radiation, in percent of the direct radiation, is plotted, as a function of the area of the diaphragm in cm².

1) *Limitation of the size of the field*

The amount of scattered radiation increases with the size of the mass of tissue, exposed to the primary beam, since each particle of this mass plays its part. Sometimes, a very considerable diminution of the scattered radiation can be obtained, by chosing the primary beam of rays no wider, *i.e.* the field irradiated no larger, than is absolutely necessary for the examination (*fig. 3a*). *Fig. 4* shows, how the scattered radiation depends upon the size of the field in the case of a stomach examination (imitated for the experiments by the irradiation of a so-called "phantom" made of "Philite"). The reduction of the field has no effect on the intensity of the primary radiation, thus $P = 1$. The selectivity Σ is therefore in this case equal to $1/S$, the reciprocal of the attenuation factor for the scattered rays. *Fig. 5* indicates the selectivity of the field-reduction method, relative to a field of 35 × 35 cm, where Σ is set equal to 1.

2) *Compression*

The mass of tissue, through which the primary radiation has to pass, can sometimes be further reduced, by local compression of the patient's body, part of the tissue being pushed to one side (*fig. 3b*). This method is particularly important in the examination of the abdomen. It only helps of course when, according to method 1), the field has been limited to the compressed part and when actual parts of the tissue are pushed aside out of the field irradiated; pressing the air out of organs filled with air has no effect, since it is not the volume, but the mass radiated, which determines the amount of scattered radiation. The advantage of this method is only fully realized, when it is combined with the following method.

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[3]) R. H. de Waard, Fortschr. Röntgenstr. **49**, 415, 1934 and **50**, 606, 1934.

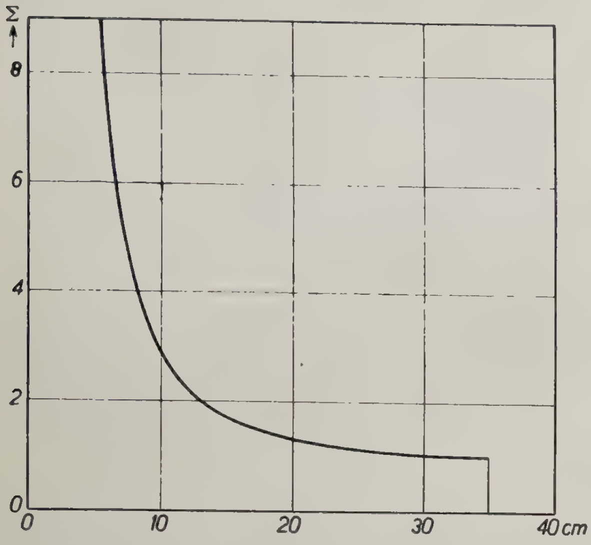

Fig. 5. The selectivity Σ (ratio between the attenuation factor for the direct radiation and that for the scattered radiation) of the method of reduction of the field. The reference field was 35 cm square. Same set-up as indicated in fig. 4.

3) *Increasing the distance between film and object*

If the film is placed not directly behind the object, but at some distance from it, it is withdrawn from the influence of a part of the scattered radiation, as may be seen from *fig. 3c* [4]). If the film is at C, all the scattered radiation from the point Q, within the angle contained between QA and QB, reaches the film; with the film at C' the angle, now between QA' and QB', is much smaller. The selectivity of this method is better, the smaller the field chosen. This may be seen from *fig. 6*, where the selectivity, measured in experiments with the same phantom as used for fig. 4, is plotted as a function of the distance between film and object, for a large and for a small field.

A great objection to this method is, that an increase of the distance between film and object results in a rapid increase of the geometrical blurring. If, for example, the patient's body is 20 cm thick, then with a distance 10 cm between film and patient the geometrical blurring u_g of a point in the centre of the patient's body is twice as great, as that with immediate contact between film and patient. Since the other two components of blurring, mentioned in the foregoing, remain the same, when we disregard for the present the increase in exposure time necessary, due to the decrease in the total intensity of radiation, the increase in the total blurring is smaller; in the example given, it amounts to about 30%. In *fig. 7* the geometrical and the total blurring are plotted as functions of the distance between film and object, for a normal stomach examination, with a focus width of 2.0 mm (full-line curves). The broken lines indicate analogous curves for the smaller focus width 1.2 mm and the necessarily longer exposure time. It may be seen, that with large distances between film and object the latter curves become more favourable, because the geometrical blurring, which then constitutes the major part of the total blurring, is less.

It may therefore be concluded, that the method discussed here is only suitable, when an X-ray tube with a small focus but with a high permissible load is used.

4) *Filters*

A certain attenuation of the scattered radiation can be obtained, by placing between patient and film a plane foil of some kind of highly absorbent metal, for instance copper or tin. The scattered rays pass through the foil for the most part obliquely, and thus cover longer distances in it, than the primary radiation. Moreover, the scattered radiation is somewhat softer, but with the normal tube voltages, used in diagnostics, this is not of much importance. In order to obtain any effect, the filter must be made

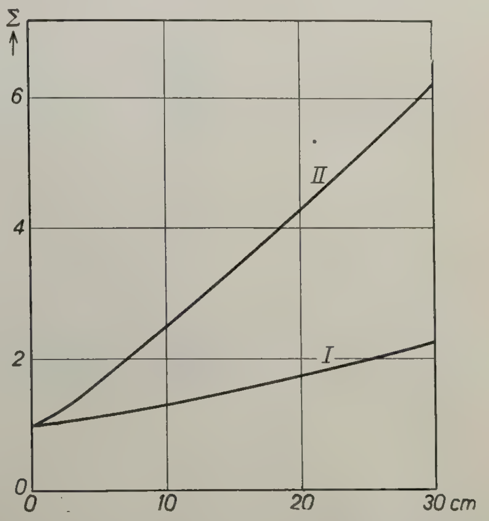

Fig. 6. The selectivity Σ of the method of increasing the distance between patient and film. The measurements were carried out with the same arrangement as that of fig. 4. Along the abscissa is plotted the distance from the phantom to the dose-meter. Curve I is for a field of 30 × 30 cm^2, curve II for 8 × 8 cm^2, on the tube side of the phantom.

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[4] H. Laurell, Acta Radiologica, **12**, 574, 1931.

rather thick and this weakens also the primary radiation very much. For a selectivity of only 2, for example, the filter has to be so thick, that the intensity of the primary beam is reduced to 20%. In general, therefore, the employment of this method offers little advantage in diagnostics [5]).

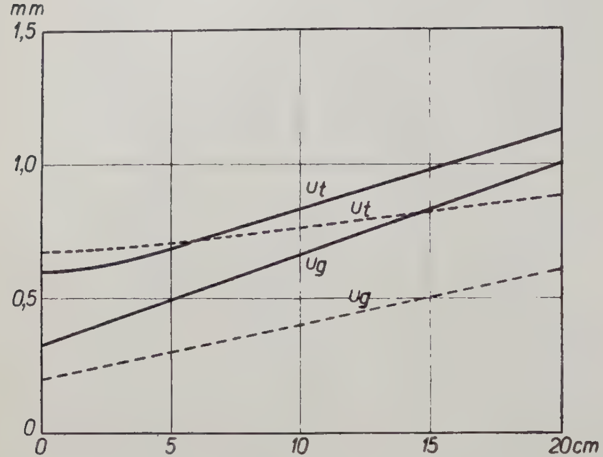

Fig. 7. The geometrical blurring u_g and the total blurring u_t, as functions of the distance in cm between patient and film, for a point in the middle of patient's body 20 cm thick. It is assumed, that there is a blurring due to the intensifying screens of 0.4 mm and a blurring due to movement of 0.3 mm for the full-line curves and 0.5 mm for the broken-line curves. The full-line curves are for a focus of 2.0 mm width, the broken-line curves for one of 1.2 mm. (The fact, that the broken-line curve u_t crosses the analogous full-line curve, is due to the uniformity condition on the left of the diagram, being approximately satisfied in the case of the full-line curves, and not on the right, while it is just the reverse in the case of the broken-line curves.)

5) *Method of slit diaphragms*

A very effective method is that sketched in *fig. 8* [6]). A slit diaphragm, with a slit of at most a few centimeters in width, is placed above and below the patient. The slits are moved along the patient, in a direction perpendicular to the slit, in such a way, that the lower slit allows the beam to pass, which has just passed through the upper slit. The adjacent parts of the object are thus exposed successively and the effect is the same, as if a number of photographs were made with a very narrow field, according to the principle of *fig. 3a.*

By making the slits narrow enough, the amount of scattered radiation can be reduced to any desired low value. A serious objection to the method, however, is the fact that the slits must move so slowly, that each strip of the film receives just as much radiation as in an ordinary exposure. The total exposure time is thus increased in the ratio of the width of the film to the width of the slit. This does not, of course, in itself lead to greater lack of definition due to movement, but the different strips of the object are photographed at appreciably different moments, so that the contours of rapidly moving organs, such as the heart or stomach, are seriously distorted [7]). Moreover, owing to the longer total time of exposure, the X-ray tube may not be loaded so heavily (for instance only by one half the power, which can be used for very short times), so that the exposure time for each strip has to be longer than for an ordinary photograph, which thus does, indeed, lead to an increase in the blurring.

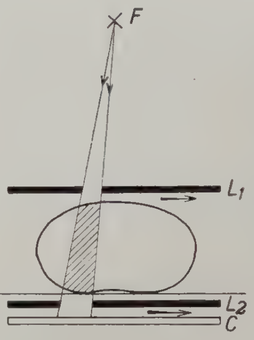

Fig. 8. Method of slit diaphragms. The two slits in the diaphragm L_1 and L_2 are moved along the object in such a way, that all parts of the latter are successively projected on to the film C. Thanks to the strict limitation of the field, each part of the film receives only little scattered radiation.

6) *The Potter-Bucky diaphragm*

One of the most important aids in counteracting scattered radiation is the **Potter-Bucky diaphragm**. In its simplest form it consists of a number of thin strips of lead, standing on their narrow edges, and placed in such a way between patient and film, that, seen from the position of the focus, each strip is as narrow as possible, see *fig. 9*. The scattered rays, in as far as their direction is not at too small an angle to that of the primary rays, strike the lead lamellae and are thereby very much attenuated. The primary rays on the other hand, thanks to the focussing effect of the lamellae, are allowed to pass quite freely except, where they strike the narrow edge of the lamellae, and except for a slight attenuation by the material between the lamellae. In order to preserve the distances between the lamellae and keep them in the correct position, they are placed in a filling material, like wood, organic synthethic material or in some cases a light metal, which is readily permeable for X-rays.

The value of this method is illustrated in *fig. 10* by four photographs of a special object with and without a Potter-Bucky diaphragm.

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[5]) To a small extent the filter effect is also obtained by the absorption of the intensifying screen placed in front of the film (see above). The filter method shows to better advantage and is therefore frequently applied in the technical examination of materials (rather than for diagnostic) where usually much higher voltages are used.

[6]) Chantraine, Röntgenpraxis **11**, 37, 1939.

[7]) This effect is entirely analogous to the familiar distortion effect, which can be obtained upon photographing rapidly moving objects, such as race-cars, with a camera with slit shutter.

Because of its practical importance and the not uninteresting particulars of the technique of this method, we shall now go somewhat deeper into the subject of the Potter-Bucky diaphragm.

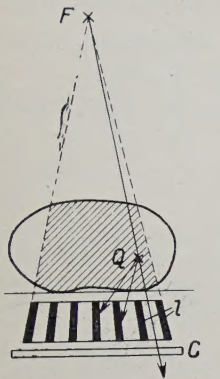

Fig. 9. Diagrammatic representation of a Potter-Bucky diaphragm. The lead lamellae *1* standing on their narrow edges and embedded in a filler, which absorbs only little X-radiation are so placed with respect to the focal spot *F* that the rays from the latter in their passage to the film *C* strike as much as possible of the open space between the lammelae. The scattered radiation from any point *Q* on the other hand is in most directions opposed by one or more lamellae.

Closer consideration of the Potter-Bucky diaphragm

Movement and focussing of the lamellae

In order to prevent the lead lamellae from producing disturbing shadow stripes in the X-ray photograph, the diaphragm is moved during the exposure in the direction perpendicular to the lamellae. The distance, over which the diaphragm must be moved, to render the shadows of the lamellae so faint as to be invisible is smaller the finer the diaphragm. In fluoroscopy, a continuous rapid movement of the diaphragm would be necessary to prevent shadow stripes on the image. Since, however, the fluoroscope screen itself causes considerable blurring of the image, diaphragms with sufficiently fine lamellae (the so-called fine-grid diaphragms with a lamellae separation of 0.5 mm or less) can be used stationary for fluoroscopy, without the stripes being disturbing.

It should be noted, that even with a moving diaphragm stripes may still appear on the X-ray photograph, namely when an X-ray apparatus with pulsating high-voltage is used, and when the frequency of the pulsations of the high voltage and the frequency with which a point of the film is shielded, owing to lead lamellae being passed at regular intervals, occur, in respect to each other, approximately in the order of whole numbers. By a suitable choice of the velocity of the motion this "stroboscopic" effect can be avoided.

In the case of a plane grid of lamellae, it will be moved in its own plane perpendicular to the direction of the lamellae. The diaphragm is then accurately "focussed" at its centre position, see *fig. 11a*. If the movement amounts to only a few centimeters to the right and left, the deviation of the focussing at the two extreme positions is not serious.

There are two methods of construction of diaphragms in which the lamellae always remain focussed, even during motion. In the one case, the lamellae are not placed on a flat plane, but along

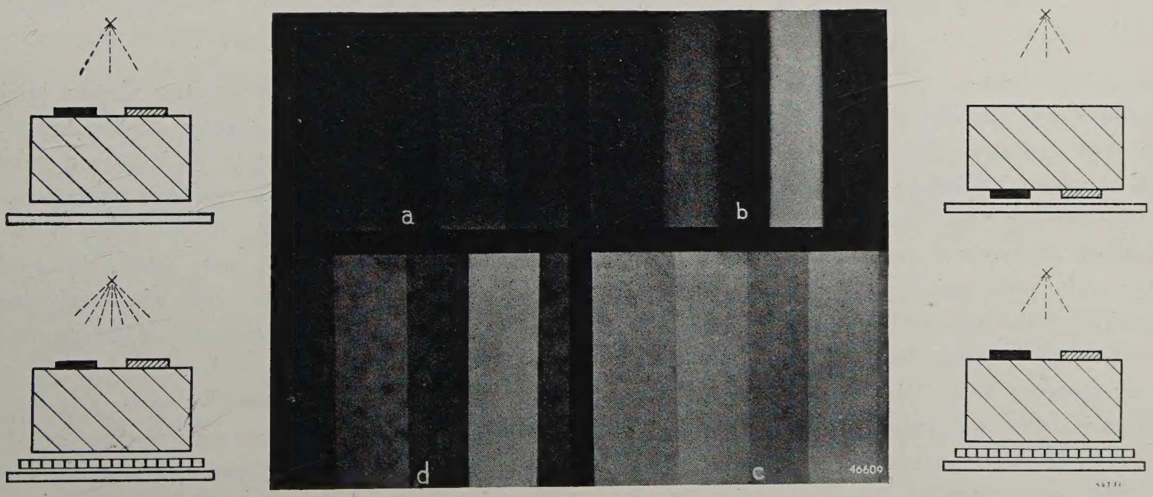

Fig. 10. X-ray photographs of a lead and an aluminium strip on a block of paraffin. *a*) The strips lay on the side of the block closest to the X-ray tube; the shadow picture is quite spoiled by the scattered rays. *b*) The strips lay between the block and the film; the shadows of the strips are now sharp, since the scattered rays, which arise in the paraffin help, as it were, to cast the shadows. The structure of the paraffin block itself, however, remains practically invisible, owing to the scattered radiation. *c*) The same as (*a*) but now with a moving Potter-Bucky diaphragm and the same exposure time. The two strips are sharp, but the picture is under-exposed. *d*) The same as (*c*) with an exposure time three times as long. Here, due to the limitation of the scattered radiation, the structure of the paraffin, characterized by numerous air bubbles, is also visible.

describing lines on the surface of a horizontal cylinder, whose axis passes through the focus (*fig. 11b*) and which can rotate about its axis. The disadvantage of this cylindrical diaphragm is, that a fairly large distance is necessary between patient and film, which increases the geometrical lack of definition, a disadvantage which also occurs with the plane diaphragms, although to a smaller extent, and which necessitates making the diaphragms as thin as possible. In the case of the second method of construction with permanent focussing, the lamellae are placed in the same plane as in *fig. 11a*, but radially, with the axis of symmetry through the focus, instead of parallel to each other (*fig. 11c*). During the exposure, the diaphragm rotates about that axis. A disadvantage, in this case, is that a white spot appears on the photograph at the position of the axis of rotation. An advantage, on the other hand, is that the diaphragm is suitable for every distance from the focus. The cylindrical diaphragm is, of course, only to be used for one distance, and the same is true of the simple plane diaphragms with parallel lamellae (even in the stationary condition). This distance is usually from 70 to 100 cm. In the case of the plane diaphragm, where a slight defocussing occurs in any case upon movement, small deviations from this distance are permissible; the transmission for the primary rays is then smaller at the edges than in the middle.

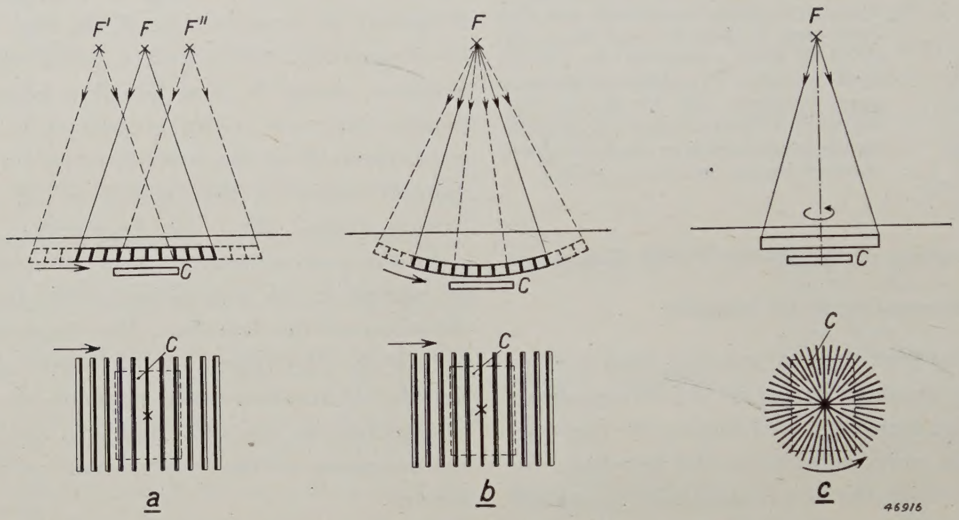

Fig. 11. Three forms of moving Potter-Bucky diaphragms. *a*) Lamellae in one plane with movement of the whole in that plane. In the position to the right or left the lamellae are focussed toward points F' and F'' respectively, instead of the focus F. The primary radiation from F is therefore more attenuated at those moments than when they are in the intermediate position. *b*) Lamellae mounted on the surface of a cylinder whose axis passes through the focus, with a swinging motion around this axis. The lamellae are always in the correct position. *c*) Lamellae placed radially in the same plane as in (*a*), about an axis of symmetry through the focus F about which the whole can rotate. The lamellae are always in the correct position.

Dimensions of the lamellae

In order to be able to give some guidance for the choice of thickness, height and distance between the lamellae, the action of the Potter-Bucky diaphragm must be considered in rather more detail. For the sake of simplicity, we shall confine ourselves to the consideration of a plane diaphragm with parallel, vertical lamellae, see *fig. 12*.

The part of the primary radiation R_p, falling between the lamellae, is transmitted almost without any weakening. But also a more or less large part of the oblique scattered rays R_s is passed unweakened, if the angle α with the primary rays is smaller, than the limiting angle α_g. With larger values of the angle α, the scattered rays would be entirely cut off, if the lead lamellae were absolutely impermeable for them. The transmission of the diaphragm, as a function of the angle of incidence of the rays, would then be as represented by curve I in *fig. 13a*. Actually, the lead lamellae may not be considered as entirely impermeable, especially as they may be very thin. With angles $\alpha > \alpha_g$, therefore, scattered radiation is indeed transmitted, though very much attenuated. The larger the angle of incidence, the more lamellae are struck by the radiation; the path in each lamellae, however, becomes shorter. The result is, that the scattered radiation transmitted at $\alpha > \alpha_g$ first decreases slowly with increasing value of α and then more rapidly. This can be represented diagrammatically by curve *II* in fig. 13*a*. This curve will, of course, also depend very much upon the tube voltage used, since the absorption in the lead decreases rapidly with increasing hardness of the rays. In *fig. 13b* the measured transmission of a fine-grid diaphragm is given for two different tube voltages. It may be seen, that these curves are not actually so smooth as the theoretical curve in fig. 13a, and, that they show slight maxima and minima.

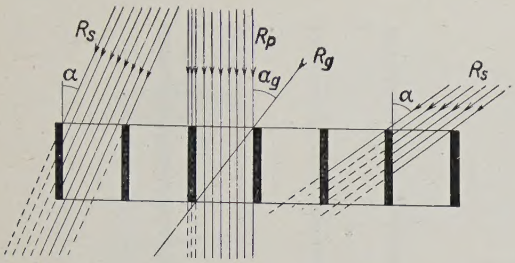

Fig. 12. Simplified Potter-Bucky diaphragm. Beams of rays striking the diaphragm at different angles are attenuated to different degrees. At angles larger than the limiting angle α_g no ray can pass through the diaphragm without attenuation.

From the curves of fig. 13, it is possible to deduce the selectivity Σ, to be obtained with a Potter-Bucky diaphragm. In this case, the selectivity can be set equal to the ratio between the transmission for the primary rays ($\alpha = 0$) and the average transmission for the scattered rays ($\alpha \neq 0$). A measure of the latter is simply the area of the surface below the transmission curve (cross-hatched in the case of curve II in fig. 13a). Thus the smaller this surface the greater the selectivity [8].

The surface below the curve becomes smaller, according as the limiting angle α_g is smaller and the more or less horizontal part of the transmission curve lies lower. Calculation shows, that the height of the flat part is determined by the amount of lead used per square cm of surface of the diaphragm, regardless, whether that lead is used in the form of thick or thin, high or low, many or few lamellae. Much lead and small limiting angle (high lamellae with narrow spaces between) are thus favourable for selectivity. But, as already stated, the transmission for the primary rays may not be reduced too much. In order to make more precise conclusions possible, we have calculated the transmission curves for several configurations of lamellae at a tube voltage of 105 kV, and they may be seen in *fig. 14. Fig. 14a* refers to the same type of diaphragms, as that with which the measurements of fig. 13 were made. The transmission curve is identical with curve *II* in fig. 13a. The selectivity calculated from this is $\Sigma = 6.3$ and the transmission for the primary radiation 72%. In *fig. 14b* the thickness of and distance between the lamellae are halved. The total amount of lead has thus remained the same, but the limiting angle is half as large. The selectivity has now risen to 7.8, while the transmission for the primary rays remains unchanged at 72 %. The greater the subdivision of the lead lamellae the greater the selectivity. In the case of the diaphragm of *fig. 14c* the distance between the lamellae and their thickness are the same as in *a*, but their height has been doubled. The limiting angle is thus equal to that in *b* but, thanks to the doubling of the amount of lead, the selectivity is considerably improved, to $\Sigma = 17$. The transmission for the direct radiation is slightly decreased, to 68%, due to the greater attenuation in the material between the lamellae (thicker layer). From the above it follows, that diaphragms *a* and *b* do not by any means represent the most favourable possibility for 105 kV, but that more lead is desirable for that voltage; for lower voltages, however, *a* and *b* may be quite suitable. In this way, for every tube voltage, the minimum amount of

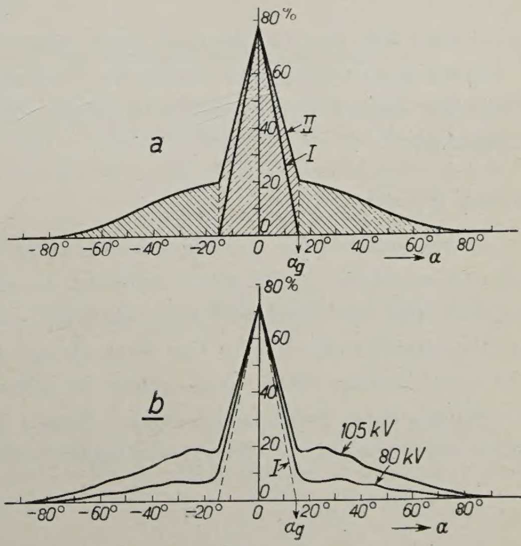

Fig. 13. The transmission of a Potter-Bucky diaphragm according to fig. 12, in percent, as a function of the angle α between the beam in question and the primary beam. *a*) Calculated for an extremely soft radiation ("zero" kV, complete absorption in the lead, curve *I*) and a hard radiation (105 kV, curve *II*). *b*) Measured, for a diaphragm with the same limiting angle α_g (ideal curve *I*), at 80 kV and at 105 kV. The total area, below each curve, is a measure of the amount of scattered radiation.

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[8] This is not strictly correct. It would only be true, if the scattered radiation were distributed spherically symmetrically, and thus the intensity of the scattered radiation falling on the diaphragm were the same from all directions. Actually, the intensity of the scattered radiation in the forward direction (small value of α) is the greatest, so that the attenuation of the scattered rays at larger angles α is of less relative importance and the actual selectivity becomes smaller than that calculated on the assumption, that all parts of the crosshatched area are of the same value. For simplicity's sake, we will adhere to this assumption; the discrepancies have no effect on the validity of the conclusions to be drawn.

lead can be calculated, which a scattered ray diaphragm should contain. The condition, thus deduced, is always easily satisfied in the case of coarse diaphragms, where the lamellae must be rather high in order to obtain a sufficiently small limiting angle. In the case of fine diaphragms, however, this condition must certainly be taken into account. Given a certain amount then, according to the above, the rule for increasing selectivity is, that the lamellae should be as thin as possible. The extra advantage is then obtained, that the disturbances due to stripes on the picture are less troublesome and easier to avoid. A limit is set to the reduction in the thickness of the lamellae mainly by difficulties in constructing the diaphragm.

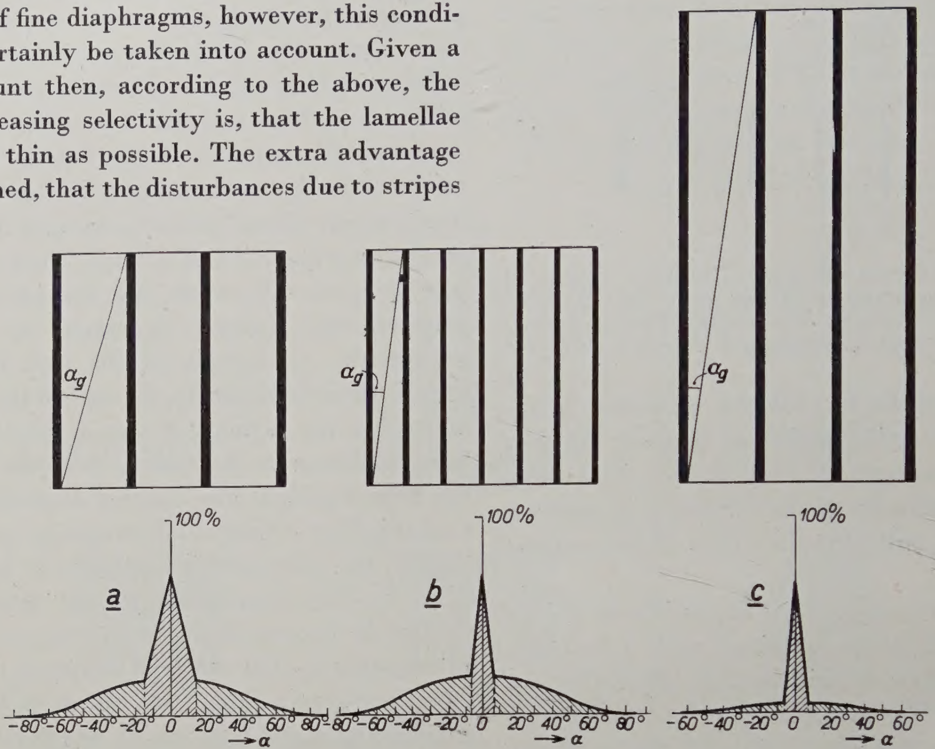

Fig. 14. Diagram of the form and spacing of the lamellae for three different Potter-Bucky diaphragms, and corresponding transmission curves for 105 kV. While *a*) and *b*) do not differ very much in quality, diaphragm *c*) proves to be considerably better. The calculated selectivity Σ is for *a*) 6.3, for *b*) 7.8 and for *c*) 17, while the primary radiation is attenuated to 72, 72 and 68 percent respectively.

Concluding remark

It is of importance for practical application to note, that none of the methods considered, is able to eliminate the scattered radiation entirely, but that, on the other hand, most of the methods can be used in combination with each other to obtain better results than with one alone. Thus, for example, even when a Potter-Bucky diaphragm is used, the field irradiated can always be made as small as possible. In connection with the method of compressing the tissue, it has already been stated, that a combination with the method of increased distance between object and film is desired. The method of the two moving slits can very well be combined with the application of the Potter-Bucky diaphragm, with the lamellae perpendicular to the direction of the slits, etc. Having regard to the drawbacks attaching to some of the methods, such as possible stripes with the Potter-Bucky diaphragm, increased blurring, when increasing the distance between object and film, distortion with the moving slits, etc., the doctor must decide from case to case, which combination of methods for eliminating scattered radiation is most suitable.